

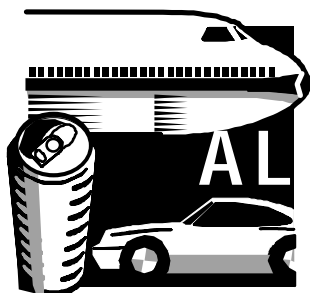
Aluminum Industry Technology Roadmap

The Aluminum Association, Inc.

May 1997

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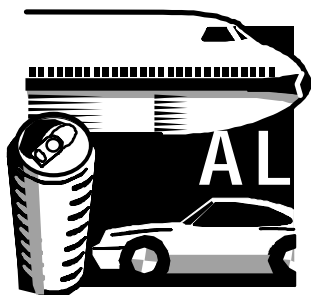
Foreword

The U.S. aluminum industry has undertaken a bold technology planning initiative to position itself to compete effectively in global markets. With the help of the U.S. Department of Energy and the Aluminum Association, the aluminum industry has developed this technology roadmap to respond to new market opportunities and challenges. The roadmap will help align the technological resources of industry and government to meet the future demands of established and emerging customers.

In early 1996, under the leadership of the Aluminum Association, the industry published *Partnerships for the Future*, which set forth its long-term vision of how to maintain and build the competitive position of the U.S. aluminum industry. The industry reaffirmed its commitment to this vision by forming a partnership with the Department of Energy that was signed by Secretary of Energy Hazel O'Leary and Aluminum Association President David Parker in October 1996. This Aluminum Industry Technology Roadmap represents the next step in the process to develop specific technology strategies for achieving long-term aluminum industry goals.

The Aluminum Industry Technology Roadmap draws from three documents that were prepared as part of an overall planning effort. The *Partnerships* document provides the strategic framework for the Roadmap and helps outline the major trends and drivers affecting technology change within the aluminum industry. Information on energy use and environmental characteristics of the aluminum industry was drawn from the *Energy and Environmental Profile of the U.S. Aluminum Industry*, planned for publication in mid-1997. The majority of the Roadmap, however, is based on the results of an industry-wide workshop that was held in November 1996. The results of that workshop are documented in *Aluminum Technology Roadmap Workshop*, published in February 1997.

This roadmap is an initial effort to provide the critical link between the broadly defined strategic goals contained in *Partnerships* and the detailed research portfolio that will be pursued through cooperative R&D partnerships. It is meant to be a dynamic document that is reevaluated at regular intervals to incorporate new market and technical information and to ensure that the research priorities remain relevant to customer needs.



1 Overview

The Challenge

In the next century, technology will hold the key to improving the quality of our lives and resolving long-standing conflicts between economic goals and resource constraints. The pace of technology change is accelerating as our global economy stimulates vigorous competition for new products, and new scientific discoveries are rapidly put to use. In response, consumer expectations for technology have increased dramatically, placing greater demands on the application and performance of materials.

Aluminum's unique properties -- its light weight, high strength, and resistance to corrosion -- make it an ideal material for use in conventional and novel applications. Aluminum has become increasingly important in the production of automobiles and trucks, packaging of food and beverages, construction of buildings, transmission of electricity, development of transportation infrastructures, production of defense and aerospace equipment, manufacture of machinery and tools, and production of durable consumer products. As demand for more technologically complex and ecologically sustainable products increases, opportunities for aluminum will continue to expand.

While the opportunities are growing, aluminum must continue to compete with various materials that offer lower cost or other competitive advantages. Aluminum companies must continue to innovate to provide customers with better enabling technologies and superior materials with unique properties. Aluminum manufacturers must explore new process technologies to drive down production costs and make aluminum more competitive. Over the next two decades, investment in research and technology development may likely be the most important factor in product competitiveness.

Leaders in the U.S. aluminum industry recognize both the opportunities and challenges they face as they enter the 21st century. They also recognize that success in the changing dynamics of competitive global markets will require new business strategies that align technology investments across industry and government. In a recent assessment of industry's technology needs, the Council on Competitiveness determined the formation of R&D partnerships to be the single most important step toward meeting tomorrow's technology and market challenges.

The Response

Working through the Aluminum Association, the aluminum industry has teamed with the U.S. Department of Energy's Office of Industrial Technologies (DOE/OIT) to address issues of competitiveness, the environment, and energy use from a long-term perspective. The aluminum industry believes that continued global leadership in materials markets will require the combined talents and resources of industry, universities, and government laboratories. By forging new partnerships, aluminum companies can use their resources more effectively to boost productivity, increase growth, and enhance environmental performance.

In 1994, the aluminum industry began examining its long-term technology needs by outlining a vision of its future market, business, energy, and environmental goals. Although the industry had limited experience with cooperative research and development, by early 1996 it had converged on its major market and technology goals. Under the leadership of the Aluminum Association and with assistance from the DOE/OIT, the industry published *Partnerships for the Future*, which set forth its long-term vision of how to maintain and build the competitive position of the U.S. aluminum industry in world markets. The industry reaffirmed its commitment to work cooperatively by forming a Compact with the Department of Energy that was signed by Secretary of Energy Hazel O'Leary and Aluminum Association President David Parker on October 9, 1996.

This industry/government partnership enables the aluminum industry and the Federal government to align their research and development efforts to meet common objectives.

In the Fall of 1996, the aluminum industry began working to develop this *Technology Roadmap*, a document that outlines the overall technology strategy for achieving industry goals and establishes a focused research and development agenda for aluminum. The roadmap differs from similar research planning efforts in that it requires all research to be linked in a coordinated framework to address a variety of technical and market issues. An important feature of the aluminum roadmap is that it reflects the needs of the entire industry, including primary and secondary aluminum producers, manufacturers of semifabricated products, and end-use customers, as well as the research community. (The market sector dealing with cast aluminum components is not included in this roadmap, but is covered in a separate industry initiative on cast materials). While complementary business strategies may be needed to achieve all industry goals, the roadmap addresses the *technology* strategy of the industry.

The Technical Advisory Committee of the Aluminum Association began the roadmapping process by translating the broad strategic goals contained in the *Partnerships* document into a set of specific performance targets (shown in Exhibit 1-1). These performance targets helped to clarify the key technology requirements that reflect the major concerns of the industry: cost and productivity,

Exhibit 1-1. Industry-Wide Performance Targets

Cost and Productivity Targets

- Reduce the costs associated with metal production by 25%.
- Reduce the cost ratio of aluminum-to-steel to less than 3-to-1 for auto applications.
- Increase capital productivity of the aluminum industry.
- Reduce product costs and product lead times through process re-engineering.

Market Targets

- Increase aluminum use in auto markets by 40% in 5 years.
- Increase aluminum use in non-auto transportation markets.
- Increase aluminum use in infrastructure markets by 50%.
- Increase aluminum use in building and construction markets.

Environmental Targets

- Recycle and treat all types of aluminum wastes.
- Increase recyclability of aluminum scrap.
- Achieve 80% wrought recycling of autos by 2004.

Energy Targets

- Increase the current efficiency of the Hall-Héroult cell process to over 97%.
- Reduce overall energy intensity of aluminum production.

Health and Safety Targets

- Increase the health and safety of workers.

Workforce Targets

- Increase the level of training and knowledge of the existing aluminum industry workforce.

development of new markets, environmental protection, energy efficiency, health and safety, and workforce. This effort was followed by an *Aluminum Technology Roadmap Workshop* that was jointly sponsored by the Department of Energy and the Aluminum Association in November 1996. Its purpose was to build an industry-wide consensus on the essential research needed to meet aluminum industry performance targets and goals.

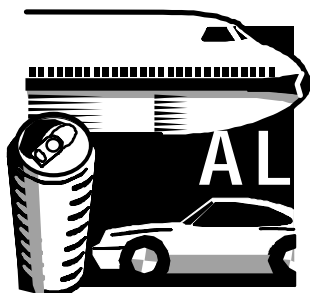
The *Aluminum Technology Roadmap Workshop* brought together 37 experts from the aluminum industry, its customer industries, universities, and government research programs. The two-day workshop addressed the technology barriers and research needs of the entire industry including primary, semifabricated, and finished product sectors. The core of the workshop was four facilitated work sessions in which participants explored in detail the technology requirements of primary products, casting, rolling and extrusion, and finished products. These work sessions resulted in over 160 research ideas of which about half were considered to be priority items. Exhibit 1-2 lists the top research thrusts for each work group.

The work group participants also analyzed the research ideas to help describe key characteristics that are important for research planning. Each group analyzed the appropriate time frame in which each research thrust is expected to yield benefits. Research activities were assigned to one of three time frames: near- (0-3 years), mid- (3-10 years), and long-term (beyond 10 years). In some cases, the participants also indicated the anticipated roles for industry and government in supporting selected research activities. Finally, participants identified important interrelationships and linkages among research activities within their industry segment.

The results of the workshop are described in a document entitled *Aluminum Technology Roadmap Workshop* (AA 1997) and serve as the foundation of this technology roadmap. It is an initial effort to provide the critical link between the broadly defined strategic goals contained in *Partnerships* and the detailed research portfolio that will be pursued through cooperative R&D partnerships. The research priorities outlined in this roadmap will be used as the basis for making new research investments by government and industry. However, the roadmap is a dynamic document that will be reevaluated at regular intervals to incorporate new market and technical information and to ensure that the research priorities remain relevant to customer needs.

Exhibit 1-2. Selected High Priority Research Needs for the Aluminum Industry

Primary Products	Semifabricated Products		Finished Products
	Casting	Rolling & Extrusion	
Conduct near-, mid-, and long-term research for anode and cathode technology	Conduct more R&D on understanding filtration mechanisms	Develop a more complete understanding of the relative strength and formability of alloys for hot rolling structure and cold rolling time temperature reductions	Fully understand the relationship of aluminum alloy composition and processing and their effects on microstructure and properties
Conduct long-term R&D on alternative reduction and refining processes	Develop an optimum “furnace” design for the future	Develop computer-based system for extrusion die design	Develop advanced forming processes of net-shape and near-net-shape components
Develop effective mathematical models	Develop fundamental information on solidification of alloys to predict microstructure surface properties and stresses and strains	Develop better understanding of customer requirements and optimize process steps accordingly	Achieve surface defect-free, continuous cast 5000/6000 sheet
Develop better understanding and models of chemical and physical phenomena in the Bayer and reduction processes	Develop low-cost inclusion sensor	Develop techniques and associated test methods for the determination of sheet formability	Design, build, and test prototype bridges
Transform aluminum process waste into usable products	Develop methods to identify and separate scrap	Conduct formability studies relating strain, strain rate temperatures, and stress state	Develop design concepts for use of aluminum in mass transit vehicles



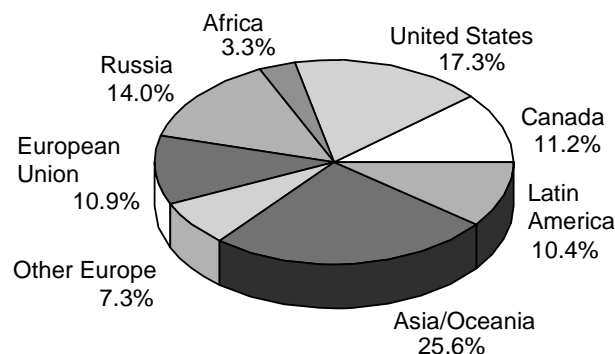
2 Primary Products Sector

The primary products sector covers the steps leading to the production of molten metal, including alumina production, reduction, and scrap pretreatment and melting.

Current Situation

Molten primary aluminum is produced by the electrolysis of alumina in the Hall Heroult process. In this process, consumable carbon anodes are used to pass the electric current into the “pot” where the electrochemical process takes place. The alumina itself is separated from bauxite, a natural ore, by the Bayer process. In the secondary aluminum industry, new or in-house scrap (generated in aluminum manufacturing facilities) and old scrap (used, discarded by the consumer, and subsequently collected) is cleaned, remelted, and refined to produce molten aluminum alloys ready for casting and shaping into semifabricated products.

The domestic primary aluminum smelting industry (SIC 3334) consists of 23 facilities operated by 13 firms with a total workforce of approximately 20,000. The secondary smelting industry operates an estimated 68 plants employing 3,600 people (EPA 1995). The majority of primary aluminum producers in the United States are located either in the Northwest or the Ohio River Valley. Most secondary smelters tend to be located in Southern California and the Great Lakes Region.



Source: The Aluminum Association, Inc.

Exhibit 2-1. World Primary Aluminum Production

Production Statistics

In 1995, U.S. primary aluminum smelters produced 3.375 million metric tons of aluminum, 17.3% of the total world production of 19.442 million metric tons (Exhibit 2-1) (AA 1996). Production of primary aluminum in 1996 in the United States was reported to be 3.577 million metric tons, an increase of about 6% over 1995 (AA 1997a).

Recycling is a critical component of the aluminum industry; in 1995, secondary refiners recovered 3.188 million metric tons of recycled aluminum, representing a little more than one-third of the total U.S. aluminum supply of 9.265 million metric tons (AA 1996).

Energy

Primary aluminum production is electricity-intensive. The current U.S. average energy

consumption for aluminum reduction is estimated to

be 15.18 kWh/kg of aluminum (Richards 1997). The lowest energy consumption that can be achieved today is about 13.0 kWh/kg of aluminum for a line of modern, high-amperage reduction cells. Production cells normally have current efficiencies ranging from 85 to 95%. Large, modern reduction cells operate with current efficiencies of 94 to 96% (Tabereaux et al. 1993).

Major energy savings are achieved through the recycling of scrap aluminum, which requires only about 5% of the energy required to produce primary aluminum.

Environment

In the past, the main industry concern for the environment was emissions of perfluorocarbons from the reduction cells. The industry has made significant achievements in reducing these emissions, and the focus of concern has shifted to carbon dioxide (CO₂) emissions. Carbon dioxide is the main component of the anode gas during the electrolysis process. It is also generated during the production of the electricity used in electrolysis, and is thus strongly dependent on the source of electric power.

The total process air emissions (excluding power plant combustion emissions) for smelting and ancillary processes for representative industry processes are estimated to be 1.56 kg/kg of aluminum, of which about 90% (1.4 kg) is CO₂ (Richards 1994). Total CO₂ releases from the unit processes of bauxite mining through the production of molten aluminum in a crucible have been estimated at 11.7 kg/kg of aluminum (Richards 1994). Combustion emissions account for approximately 70% of this total.

Major byproducts include spent potlining from primary aluminum reduction and dross/salt cake from secondary aluminum production. Spent potlining is a RCRA-listed hazardous waste, K088. The U.S. Environmental Protection Agency estimates that about 120,000 tons of K088 are generated annually. Dross and salt cake contain valuable aluminum, much but not all of which is currently recovered.

Trends and Drivers

Energy Costs

Energy is a major component of the total cost of producing aluminum. The decreased availability and higher costs of energy in the U.S. have restricted the ability of the domestic aluminum industry to compete against those regions of the world where energy resources are readily available at low costs. World-wide smelter expansions and new plant construction have been focused on nations with low-cost energy and labor resources. Canada, Russia, and several countries in South America all have relatively low-cost hydroelectric power available.

Oversupply in World Markets

Beginning in 1991, the aluminum market was faced with rapidly increased exports from the former USSR. Before its breakup, very little Russian metal appeared in Western markets. However, with the emergence of the Commonwealth of Independent States (CIS), large amounts of excess metal entered the market, causing a serious imbalance in world aluminum markets through 1993. In 1994 and 1995, demand for aluminum in Western markets increased, and the world aluminum industry has made the necessary adjustments to bring inventories to more reasonable levels.

Periodic cycles of oversupply may continue to impact the aluminum industry from time to time, especially as geopolitical restructuring continues in Eastern Europe. Typically the industry has reacted to such

challenges by deferring expansions and shutting down smelter capacity, either temporarily or permanently. Increases in capacity, however, are likely to occur as demand increases.

Government Regulations and Public Policy

Recycling was instituted by the aluminum industry itself both to save energy and because of the intrinsically high value of recovered metal. More recently, it has also been encouraged by government regulations as a means of conserving resources and reducing waste. As a result, the quantity of aluminum recycled has increased from about 0.5 million metric tons in 1960 to 3.188 million metric tons in 1995, representing about one-third of the total U.S. aluminum supply of 9.265 million metric tons. Post-consumer scrap contributed nearly half of the aluminum recovered from recycled scrap in 1995. Recyclability must become a serious consideration in the development, specification, and application of new products and their materials systems. This trend will only increase as concerns for the ecological sustainability of products, their structural materials, and manufacturing processes continue to grow and as the public becomes more knowledgeable about ecological sustainability.

Increases in capital and operating costs have been experienced by U.S. industries to meet increasingly stringent environmental standards. The Clean Air Act and its amendments, including the Clean Air Act Amendments (CAAA) of 1990, have had a significant impact on the industry, with additional impacts expected in the next several years. The U.S. Environmental Protection Agency (EPA) is currently developing emission standards for new and existing sources of hazardous air pollutants based on “maximum achievable control technology” (MACT). The proposed new standards would apply to emissions of hydrogen fluoride (HF) and polycyclic organic matter (POM), both of which are emitted during primary aluminum production. EPA is also working on the development of MACT-based performance standards for secondary aluminum production. A number of other regulations under consideration by EPA directly affect the aluminum industry.

In April 1996, EPA promulgated treatment standards for hazardous wastes from primary aluminum production under Phase III of its Land Disposal Restrictions program. As of July 1997, primary aluminum producers will have to ship and treat spent potlining. Hazardous constituents in these wastes will also be required to meet universal treatment standards (UTS) before disposal in a land-based unit.

Economic Structure

While U.S. primary aluminum production grew steadily in the first 60 years of this century, changes in economic structure have restrained the rate of such growth over the past two decades. One significant change has been the shift in the U.S. towards a service economy and away from manufacturing, relying more on imports for goods such as automobiles that use large quantities of aluminum. This has restrained the growth of domestic demand for primary aluminum. The primary sector has also been affected by the very positive trend of increased use of secondary, recycled aluminum in domestic markets.

Performance Targets

The performance targets set by the industry for the primary products sector are shown in Exhibit 2-2. One of the major goals, or performance targets, defined for the sector was to reduce the energy (electricity) intensity of smelting. Other goals included improving the productivity of the Bayer process, reducing and ultimately eliminating anode-related CO₂ emissions, reducing costs, improving metal quality, enhancing recycling, and increasing the use of wastes and byproducts.

Technology Barriers

There are a number of barriers that prevent greater energy efficiency, productivity, metal quality, and environmental performance of primary and secondary aluminum production. These barriers are shown in Exhibit 2-3 organized by topic.

Exhibit 2-2. Performance Targets for the Primary Products Sector

1. Improve the performance of the Hall-Héroult cell
 - Achieve an average cell efficiency of 97% on an annual basis
 - Reduce the energy intensity of aluminum production to 13 kWh/kg using retrofit technology (near to mid term)
 - Reduce the energy intensity of aluminum production to 11 kWh/kg (long term)
 - Reduce capital cost of aluminum production to \$2,500 per annual metric ton of capacity
 - Cost-effectively minimize the generation of perfluorocarbons (PFCs)
2. Improve Bayer process productivity by approximately 20%
3. Reduce/eliminate CO₂ emissions during smelting
4. Enhance aluminum recycling technologies
 - Increase education on existing technologies
 - Minimize or eliminate formation/landfilling of dross and salt cake
5. Improve metal quality
 - Adapt to using alternative sources of carbon
 - Reduce impurities in recycled alumina
6. Reduce the cost of aluminum reduction by 25% using alternative technologies
7. Develop new uses for wastes and byproducts from aluminum processes

Most of the barriers facing recycled materials fall into two major areas -- scrap pretreatment and use of byproducts. Problems with scrap sorting, separation, cleaning, and other pretreatment processes inhibit the

increased use of different types of scrap and also contribute to metal quality problems because of the inability to completely remove impurities. Lack of comprehensive information on the characteristics of byproducts is a major barrier to increased use of these materials. Cost is considered a barrier both to increased utilization of aluminum itself as well as its byproducts.

Productivity is the primary issue in the Bayer process. The productivity (i.e., yield and rate) of the Bayer process is limited by factors such as the rate of trihydrate precipitation and the temperature and pressure constraints of the digestion process. A lack of basic knowledge in several aspects of the Hall-Héroult reduction process inhibits efforts to increase the energy efficiency of aluminum production. These areas include anode/cathode technology, bath chemistry, new cell designs, and energy losses from the cell.

In the area of alternative processes, there is a critical lack of emphasis on coordinating the entire aluminum production process (from refining or scrap melting through fabrication) to address issues of metal quality, energy efficiency, and productivity. The reliance of the reduction process on electrical energy, rather than chemical energy, may limit the cost-effectiveness of the reduction process.

The inability to accurately model, measure, and control many key parameters and phenomena during refining and smelting presents a significant barrier to several of the performance targets, particularly improved Bayer process productivity and improved reduction cell performance. Current process models are insufficient for optimizing the refining and reduction processes. Reliable and cost-effective sensors are not available to measure and control several critical operating parameters. The materials and other problems preventing the development of key measurement techniques and sensors for these processes represents another barrier.

Institutional factors also appear to contribute significantly to the lack of progress towards the performance targets. These factors include insufficient communication among the different stakeholders and a lack of knowledge about the results of previous R&D efforts.

Exhibit 2-3. Technology Barriers in the Primary Products Sector

Bayer Process	Reduction Processes	Alternative Processes	Recycled Materials	Enabling Technologies/ Measurements and Controls	Institutional Barriers
Inability to significantly increase rate of alumina precipitation	Hydrocarbon capture systems for Soderberg are insufficiently effective	Lack of emphasis on combining of units (e.g., refining and reduction)	Volume vs. price for recycled materials	Lack of process optimization models	Lack of institutional communication
No comprehensive database on chemical properties of pure alumina	High costs of reduction equipment	Lack of systems approach to overall process - Metal quality	Inability to qualify recycled materials into each part of process	- Use current models for future improvements - Need 3-D models (not only 2-D)	Lack of researcher awareness of current assets
High capital investments of Bayer process	Lack of robust understanding of bath chemistry	No method of low-temperature electrolytic production of solid aluminum	High cost of scrap	Inadequate process tools and controls for reduction cells	Lack of knowledge of previous research
Inability to increase thermal efficiency of Bayer process	Inability to raise thermal efficiency of reduction	Need to maximize use of chemical vs. electrical energy	Need for profitable return on byproducts	Lack of sensor materials	Lack of coordination between all players
Need higher temperature and pressure digestion	Reduction cell external losses are too high (voltage)		Limited awareness of recycling technology by many users and producers of aluminum (especially among small recyclers)	- Method to continuously measure Al_2O_3 concentration - Material to withstand cryolitic exposure	- Partnerships - Government assistance
Relatively low yield of Bayer process	Lack of economical method to change out buswork on older cells				Lack of regulatory cooperation (spent potliner)
Lack of control system for Bayer process - Trihydrate precipitation	Relatively low efficiency of petroleum coke calcination		Inadequate knowledge of waste stream composition	Need control strategies to go with new sensors	Lack of agreement on specification within industry
Lack of cost-effective raw material alternates to bauxite as the source of alumina	Lack of basic materials knowledge on dimensionally stable anodes		Lack of pre-treatment methods for emerging types of scrap		Government role in research is unclear
Adverse impact of excess impurities	Need improved cathode/wetted cathode research		Lack of recycling technologies - Removal of organics (Bayer)		
	Lack of new cell design concepts		Lack of alternatives to mechanical separation		
	No economical separation technique to remove impurities from		Lack of sophisticated		

Research Needs

Research needed to overcome these barriers that were organized into the same categories used in the preceding analysis (Exhibit 2-4, with the highest priority needs boldfaced). Aluminum industry needs in process modeling and sensors and controls can be addressed through studies and R&D projects. The studies include the development of a systems approach to materials design in order to optimize performance, the development of design models for new and existing processes, and the development of models to understand the basic physical and chemical phenomena (e.g., gas-driven circulation, mass transfer, magnetism, and electrochemistry) occurring in the reduction cell. These studies are seen as critical to increasing the productivity and efficiency of reduction.

Enabling technology needs include inexpensive continuous or semi-continuous sensors for measuring superheat, alumina concentration, and temperature in reduction cells; control technology (particularly feed-forward, real-time systems) to use with the sensors; and low-cost, durable coatings and materials for use in the harsh environments found in the Bayer process. Specific R&D needs for the Bayer process itself focus on the ability to operate the Bayer process at high caustic concentrations, thus improving productivity. A related need is the development of suitable materials and a better understanding of the seeding process and trihydrate precipitation under these conditions. In addition, process changes to enable digestion to take place at higher temperatures and pressures would directly affect Bayer process productivity.

One of the most critical needs of primary aluminum production is for a variety of near-, mid-, and long-term R&D activities on anode and cathode technologies. These activities should focus on the development of new materials (e.g., for inert anodes/cathodes), processing methods for these materials, experimental design for materials selection, and wetted cathode technology. Using a systems approach to design dimensionally stable cells and to optimize materials use for internal control of the cell could yield cell efficiency improvements within the next ten years. In addition, the performance of signal analyses on the cell voltage in potlines could yield information that could be used to better understand and control the cell.

In reduction processes, R&D is needed to improve both cell efficiency and metal quality. For example, a better understanding is needed of how changes in the raw materials used to make carbon anodes (e.g., higher sulfur, higher ash) will affect the performance of the anodes. Along a parallel path, new non-carbon anodes need to be developed, eliminating CO₂ emissions and improving cell performance. There is a nearer term need to develop inhibitors for air burning of anodes that do not adversely affect metal quality. There is also a strong need for a method to extract impurities from the reacted alumina in the dry scrubbers used to control emissions from reduction cells.

Another of the most critical needs is for long-term R&D on alternative reduction and refining processes. This includes entirely new ideas for producing aluminum -- for example, direct reduction type processes or processes that totally eliminate electrolytic reduction. Directly related to this is R&D to bypass intermediate refining steps. A coordinated effort covering both refining and reduction is recommended to optimize the cost/benefit of using current or alternative raw materials. Cost-benefit analyses of kaolin and other alternative sources of alumina could contribute toward the ultimate goal of reducing production costs.

In the area of recycled materials, there is a need for studies to establish baseline data on the character and composition of waste streams from aluminum production processes. There is also a need to develop technologies to cost-effectively convert various wastes into usable feedstock. Specific wastes include salt cake and spent potlining. A method of qualifying materials (in a regulatory sense) from spent potlining is needed, as are new technologies that minimize or eliminate the formation of dross and salt cake, one of the sector's performance targets.

**Exhibit 2-4. Major Research Needs in the Primary Products Sector
(Highest Priority Needs Boldfaced)**

Bayer Process	Reduction Processes	Alternative Processes	Recycled Materials	Enabling Technologies
<p>Develop materials and processes to allow operation of Bayer process at high caustic concentrations</p> <p>Develop better understanding of trihydrate precipitation process under high caustic concentration</p> <p>Develop alternative calcination processes to raise thermal efficiency of Bayer process</p> <p>Develop higher temperature and pressure digestion processing</p> <p>Apply cogeneration to Bayer process on a more widespread basis</p>	<p>Conduct near-, mid-, and long-term R&D for anode and cathode technologies</p> <ul style="list-style-type: none"> - Materials - Materials processing - Experimental design for materials selection - Wetted cathode - Non-carbon (inert) anodes <p>Conduct R&D in alternate cell concepts</p> <ul style="list-style-type: none"> - More effective hydrocarbon capture systems - Method to change out buswork economically on older cells <p>Develop method to extract impurities from alumina used in dry scrubbers</p> <p>Examine alternative carbon sources; learn to cope with new anode carbon materials (high sulfur, ash)</p> <p>Perform signal analysis of cell voltage (noise) to improve control of cell</p> <p>Optimize materials and management for thermal control of cell</p> <p>Develop more robust bath chemistry</p> <p>Develop cost-effective, low-resistance, external conductors</p> <p>Conduct R&D on cell capable of performing effectively with power modulations (e.g. off-peak power)</p> <p>Conduct R&D in advanced refractory materials for the cell</p> <p>Systems approach for designing dimensionally stable cells</p>	<p>Develop durable pump to recirculate molten salt</p> <p>Bypass intermediate refining steps (part of long-term R&D of alternative refining processes)</p> <p>Perform cost-benefit analysis of the use of kaolin and other alternative sources of alumina</p> <p>Coordinate alumina/reduction effort to optimize cost benefit of raw materials or alternative raw materials</p> <p>Conduct R&D on electrolytic production of solid aluminum</p> <p>Conduct long-term R&D on alternative reduction and refining processes</p> <ul style="list-style-type: none"> - Closed-loop production plant (products and salable by-products) - Use of chemical vs. electrical energy 	<p>Develop alternative pretreatment technologies for scrap</p> <p>Turn aluminum process waste into usable feedstock</p> <ul style="list-style-type: none"> - Salt cake recycling or reuse - Separate materials from waste streams <p>Develop lower-cost aluminum purification technologies</p> <p>Characterize composition of waste streams</p> <ul style="list-style-type: none"> - Statistical analysis of composition and character of waste streams from smelters by region and cell type <p>Qualify recycled refractory materials from spent potlining</p> <p>Critique U.S. recycling infrastructure</p> <p>Develop new melting technologies (such as vacuum or inert systems) that minimize or eliminate the formation of dross and salt cake</p>	<p>Develop rapid scan method for determination of metal composition</p> <p>Develop fuzzy-logic, feed-forward, neural network, real-time process control</p> <p>Develop inexpensive continuous/semi-continuous sensors for superheat, alumina, and temperature measurement</p> <p>Determine how materials can be designed for a system</p> <ul style="list-style-type: none"> - Control optimization - Design vs. testing <p>Develop effective mathematical models</p> <ul style="list-style-type: none"> - Concerted effort for design - Design optimization <p>Develop family of low-cost, durable coatings and materials for Bayer equipment under high caustic conditions</p> <ul style="list-style-type: none"> - Corrosion resistant, abrasion resistant - High temperature <p>Develop better understanding and models of reduction phenomena</p> <ul style="list-style-type: none"> - Gas-driven circulation - Mass-transfer - Magnetism - Electrochemistry <p>Use state-of-the-art tools to re-examine processes</p>

Finally, because of the significant impact of electric power costs on the total cost of producing aluminum, a realignment of the capacity, demand, and pricing of electric power in the United States could be important in bringing down production costs of aluminum.

Exhibit 2-5 illustrates the time frame (near, mid, and long term) in which the various R&D activities are expected to be accomplished, assuming no constraints on R&D funding. The linkages between the various activities are also shown in this exhibit.

Performance Target 4 (enhancement of aluminum recycling through increased education on existing technologies) is expected to be achieved in the near term (next three years). Over the next three to ten years, several other performance targets could be achieved, including:

- Target 1 - Reduce energy intensity of aluminum production to 13 kWh/kg using retrofit technology
- Target 2 - Improve Bayer process productivity by about 20 percent
- Target 4 - Enhance aluminum recycling technologies by minimizing dross and salt cake formation
- Target 5 - Improve metal quality

To support these targets (particularly Targets 1, 2, and 5), R&D on a number of enabling technologies (including mathematical and physical models, neural network process controls, continuous/semi-continuous sensors, and signal analysis of cell voltage) has been suggested. These technologies will affect either process design capability or the ability to design for new materials. These two areas are important for improving the efficiency and productivity of current processes as well as developing new processes for aluminum production. A greater understanding of the complex physics surrounding the smelting process, including charge transfer at the cathode surface and the undulation of the metal pad (if such pads are used in the future), will also facilitate these performance improvements.

New sensors, together with advanced control technologies, will allow the industry to measure and control key process parameters, leading to higher process efficiencies. These sensors and controls have a range of applications, covering both short-term needs and goals as well as contributing to the development of new processes.

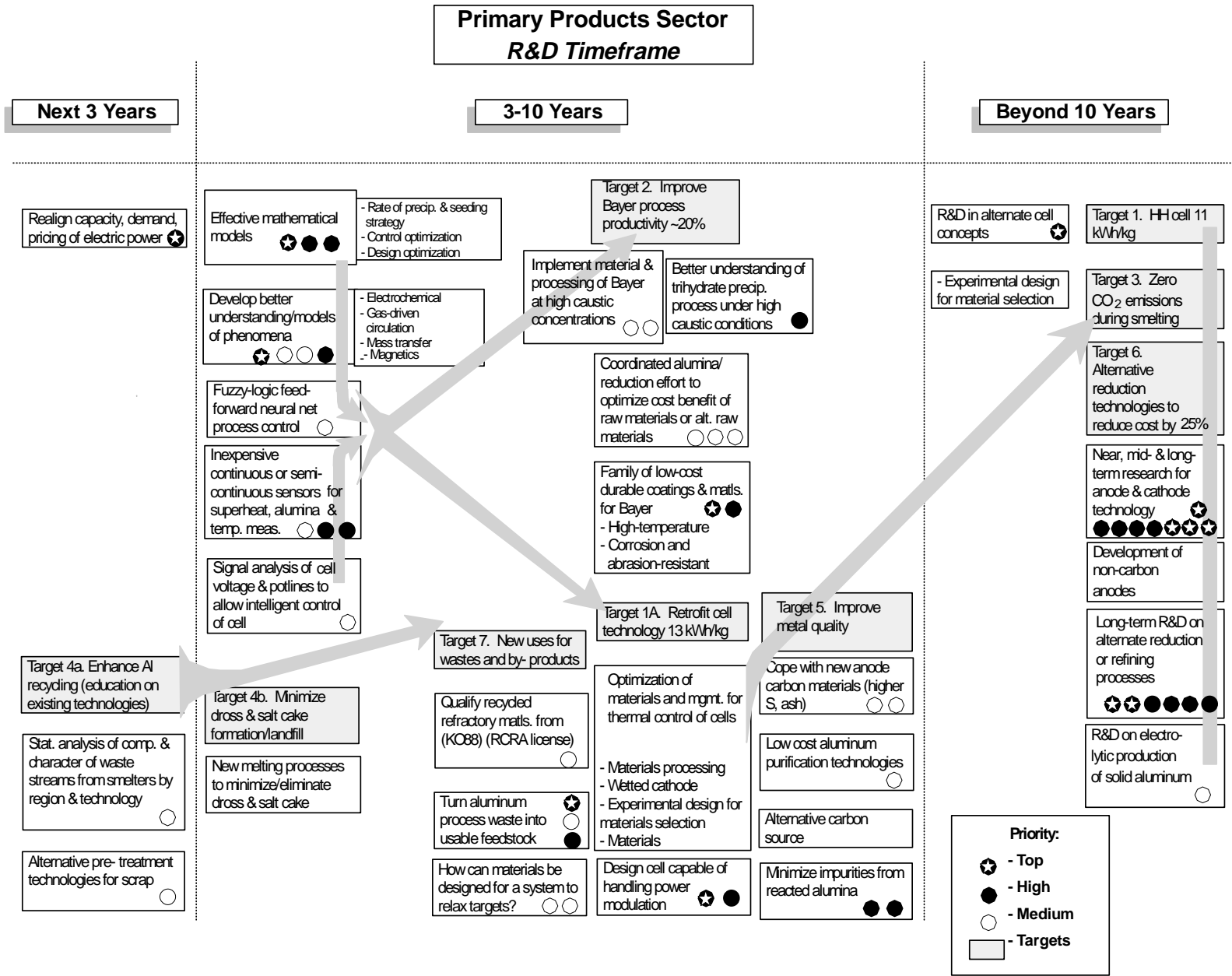
The mid-term performance target of improving Bayer process productivity by 20 percent would be supported by R&D to develop technology to allow operation of the Bayer process at very high caustic concentrations. A better understanding of trihydrate precipitation at high caustic concentrations is also needed. In addition, an understanding of the balance between the specifications of alumina from the Bayer process and of molten metal from the smelting process could lead to a more coordinated effort for identifying the best overall strategy for solving specifications problems while reducing production costs.

One of the key factors in achieving a Hall-Héroult cell average energy use of 13 kWh/kg (identified as a mid-term goal) is to optimize materials for management of internal control of the cell. Even if the energy requirements of the cell are lowered by reducing the anode-cathode space (or by other means), some method of conserving the energy in the cell is still needed. However, cell insulation is degraded by corrosion of the sidewall and bottom which creates a materials-related R&D need. Related needs are a better understanding of the best design, the development of low-cost materials, and the development of wetted cathodes.

Two performance targets related to wastes and byproducts -- minimization of dross and salt cake formation and the development of new uses for wastes and byproducts -- are considered mid-term targets. The first can

be accomplished by developing new melting processes that eliminate or minimize the formation of these wastes.

Exhibit 2-5. Research Linkages for Primary Products Sector



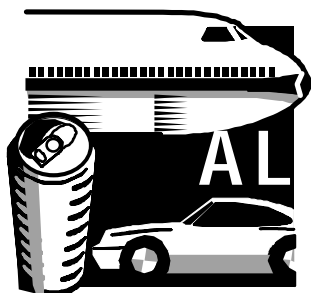
The development of economical technologies for turning aluminum wastes such as red mud into usable feedstocks for other processes could eliminate this environmental problem.

Performance Target 5 -- “Improve Metal Quality” -- consists of two main areas of emphasis. The first focuses on the changes in the existing carbon sources, including increases in impurities, sulfur, and cost, and considers effective methods of incorporating these changes. In addition, new low-cost, alternate carbon sources would alleviate some of the quality problems. The second major interest is a method to minimize or remove the impurities from the alumina that has been used for scrubbing the gases coming off of the cell. Because this alumina is placed back into the system, any impurities are also put back into the cell, which adversely affects metal quality.

From the mid term to the long term, there is a transition between making incremental improvements in existing processes and developing entirely new concepts and processes. If application of the enabling technologies previously discussed is successful, the Bayer process will likely have been taken to its practical limits. Beyond that, further improvements will be tougher to achieve and the performance targets will become more complex. The enabling technologies and materials developments will also feed into these higher-level goals. R&D for alternate cell concepts will be needed, as will entirely new ideas on how the system can be configured to maximize the energy efficiency of aluminum production and potentially eliminate carbon-based gas emissions, (e.g. CO₂) and perfluorocarbons.

Along these lines, considerable R&D on anode and cathode concepts is needed. For example, the creation of a dimensionally stable inter-electrode space between the anode and cathode would be a significant accomplishment. The development of non-carbon anodes is a further emphasis of the idea of having a dimensionally stable anode. The development of totally new, alternative processes, perhaps direct reduction-type processes, could eliminate the electrolytic reduction step. Another suggested long-term, high-risk effort is R&D to look at a route to produce solid aluminum. This would be done at very low temperatures, leading to significant energy efficiency and materials advantages. However, R&D would be needed to learn how to take solid aluminum out of the system and convert it into a usable material for downstream processing.

The nature of some of the recommended R&D activities, particularly the long-term research on anodes, cathodes, and new or alternative processes, appears to lend themselves to the idea of research consortia. The consortia could consist of aluminum companies, the Department of Energy and its national laboratories, and materials suppliers. In addition, some of the suggested mid-term R&D activities such as Bayer process research would best be handled by consortia.



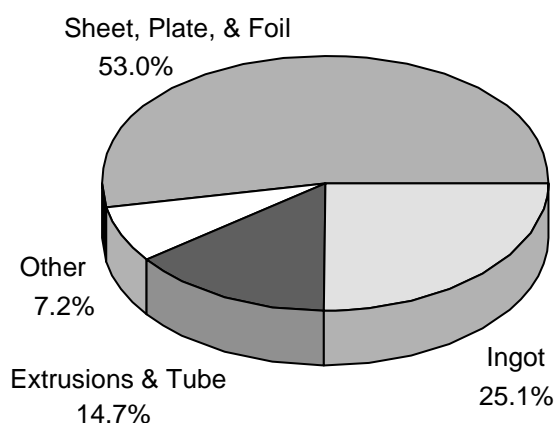
3 Semifabricated Products Sector

The semifabricated products sector covers all of the processes used to transform molten primary or secondary aluminum into any one of a number of semifabricated shapes (plate, sheet, foil, wire, tube, etc.). The **Current Situation** and **Trends and Drivers** for the entire semifabricated sector are described, followed by individual subsections for the major areas of 1) casting and 2) rolling and extrusion.

Current Situation

In the semifabrication sector, the molten primary or secondary aluminum is first typically cast into ingots, which are used as the basic charge components in subsequent remelting or mechanical operations. The aluminum can also be continuously cast and fed directly into a rolling mill. Hot and cold rolling processes are used to roll the aluminum into plate, sheet, or foil. Drawing and extrusion processes are used to produce tube, wire, or other similar products. Other semifabricated products include forgings, castings, and elemental and alloyed powders; however, the latter products were considered beyond the scope of this roadmap.

As shown in Exhibit 3-1, sheet, plate, and foil represented 53.0% of total shipments in 1995. Ingot for castings, destructive uses (i.e., rocket propellants), and exports accounted for 25.1%, and extruded products and tube shipments were 14.7%.



Source: The Aluminum Association, Inc.

Exhibit 3-1. Industry Shipments by Major Products

Trends and Drivers

The same forces that have influenced the primary sector (overcapacity in world markets and economic conditions) have also had an impact on producers of semifabricated products. Supply for semifabricated products has exceeded demand around the world in recent years. The resulting global competition has created substantial pressure on U.S. production. This pressure has forced the industry to focus on increasing productivity and value in aluminum products. Incentives for further improvement are also provided by the U.S. automotive industry's pressures to combine their increased use of aluminum with lower life-cycle costs.

Advanced manufacturing processes and technologies have become much more prevalent in the past decade. Many semifabricated producers

have been working to increasing productivity and reduce costs in rolling, forging, casting, and

extruding. First-generation models, simulations, and expert systems have been developed, and computer-enhanced manufacturing technologies have been applied, primarily in the rolling area.

Government regulations are also helping shape the aluminum semifabricating industry of the future. With the relaxation of tariff barriers, strongly supported by the U.S. aluminum industry, the location of new manufacturing resources will be increasingly determined by access to new markets and favorable labor and energy costs, as well as regional tax benefits. North American companies may benefit from investment in Eastern Europe and Asian capacity as a way of participating in these markets. Trade in semifabricated metal during the next decade in these regions is likely to increase.

CASTING

Casting Performance Targets

Exhibit 3-2 shows the performance targets defined for casting products. As shown in Exhibit 3-2, the industry has determined that additional targets need to be set in a number of casting technical areas.

Exhibit 3-2. Performance Targets for Casting

- Increase reliability of manufacturer operations to 95%
- Improve process control
 - Better models of plant operations
 - Temperature sensors for rolling operations
 - Real-time measurement of molten metal composition
 - Pressure sensor for container/die
- Develop better understanding of strip casting
 - Models of materials properties

Areas in Which Targets Need to be Set

- Continuous casting processes (strip, slab, wire, bar, etc.)
- Melting
- Melt-loss prevention
- Skim treatment/avoidance
 - waste disposition/avoidance (salt cake, nonmetallic product)
- Scrap recycling
 - in-plant and exterior
- Safety and health
 - molten metal handling
 - fluxes and emissions

Casting Technology Barriers

There are a number of technology-related barriers that prevent the immediate attainment of the casting performance targets. They may be classified into five major categories: skim and dross, casting, metal processing and treatment, melting and recycling, and crosscutting, as shown in Exhibit 3-3. The creation of skim and dross in the casting process is a general problem. An ideal process would eliminate skim and dross entirely. Until such technology exists, better methods for treating/removing skim and dross will need to be developed. One barrier to making better use of skim and dross is the lack of industry coordination in developing applications for nonmetallic product (NMP).

Casting barriers encompass both process control problems and safety problems. “Bleedouts” are a problem, particularly in

direct chill casting. The lack of aluminum solidification models is a major barrier to process improvements. Currently there is not enough fundamental understanding of solidification processes and related mechanisms. Another problem is the lack of technology to feed molten metal without turbulence. Progress made by applying filtration and purification processes can be erased by recontamination in the ingot head. A widespread safety concern in aluminum casting plants is aluminum-water explosions. To prevent these

explosions, a complete understanding of the conditions that trigger the explosions and why certain coatings may prevent explosions is needed.

Exhibit 3-3. Technology Barriers in Aluminum Casting Processes

Skim and Dross	Casting	Metal Processing and Treatment	Melting and Recycling	Crosscutting
<p>Lack of understanding molten aluminum/oxygen reactions</p> <p>Minimizing oxidation of aluminum/magnesium alloys (elimination of beryllium)</p> <p>Need for skimming</p> <p>Lack of alternative dross treatments</p> <p>Lack of industry coordination for developing NMP applications</p>	<p>No way to prevent “bleedouts” during direct chill casting</p> <p>Limited means of detecting bleedouts in billet casting</p> <p>Lack of understanding of mechanisms of cracking as a function of alloy</p> <p>Poor water quality and uniformity (around the mold)</p> <p>Incomplete understanding of why certain coatings prevent aluminum-water explosions</p> <p>Incomplete understanding of the conditions that trigger aluminum-water explosions</p> <p>No way to prevent recontamination of metal in ingot head</p> <p>Too many cavities and voids in the sows--inability to practically determine sow soundness</p> <p>Insufficient understanding of the aluminum solidification process; difficult to model</p> <p>Art of casting is being lost as workers retire</p> <p>CONTINUOUS PROCESSES</p> <p>Limited ability to control degree and uniformity of heat extraction</p> <p>No methods for continuously casting more high- alloyed products</p> <p>No way to do in-line surface removal for continuous casting</p> <p>Cannot cast all alloys and sizes through horizontal</p>	<p>Lack of economical alternatives to chlorine fluxes for magnesium removal</p> <p>Too many impurities (e.g., lead)</p> <p>Need better impurity removal</p> <ul style="list-style-type: none"> - Inclusions - Iron 	<p>Lack of methods to identify scrap composition</p> <p>No way to separate scrap by alloy</p> <p>Low fuel efficiency in melting and holding furnaces</p> <p>Too much contamination in purchased scrap</p> <p>Secondary alloys based on decades-old specifications</p> <p>Sub-optimal scrap recycling technology</p> <p>Inefficient furnaces for scrap heating and waste heat recovery</p> <p>Temperature stratification and alloy segregation</p>	<p>Insufficient system level thinking</p> <p>Over-reliance on remelting</p> <p>Lack of cooperation within the aluminum industry</p> <p>Segmented, operation-specific thinking</p> <p>Current processes too energy intensive</p> <p>Majority of technology based on 80-year old design</p> <p>Need process control sensors</p> <ul style="list-style-type: none"> - Lack of good sensors and controls for quality and metallurgical structures

Advances in continuous casting will be necessary to ensure the continued competitiveness of the U.S. aluminum industry. Several barriers related specifically to continuous casting include cooling limitations, a lack of methods for continuously casting higher content alloys, and the inability to perform in-line surface removal.

Technology barriers related to metal processing and treatment mainly concern the presence of impurities. Contaminants like iron, magnesium, lead and other elements, and nonmetallic inclusions, create a number of product quality problems. Scrap separation and processing are key problems in the area of melting and recycling. The ease and cost-effectiveness of aluminum recycling could be markedly improved through development of automatic methods that can achieve aluminum scrap separations on an alloy-by-alloy basis. Purchased scrap may contain contaminants that can be dangerous, such as phosphates and nitrates from fertilizers. Another problem with producing recycled metal is that the specifications for major secondary alloys are decades old. The specifications of the amounts of impurities allowed may be too conservative, thus producing a product that is higher quality than needed to meet the demands of the end-user. The furnaces currently used for melting are highly energy inefficient and are thus expensive to operate.

Crosscutting barriers cover problems that apply to casting in general, or even to the industry as a whole. Competitive forces have made it difficult for the aluminum industry to work cooperatively on processes affecting their internal production technology. For example, there are many technical areas where problems are generic and shared information could help to develop either common or proprietary solutions. This problem is aggravated by insufficient system-level thinking. Too often, research and problem-solving are approached on a segmented, operation-specific level, without considering how the system as a whole (from primary through finished product) could be improved to produce a better quality and/or lower cost product. Technological progress is often made by improving designs that are 80+ years old, rather than by creating new designs that could replace the existing technologies. This is due in part to the large capital investment in existing equipment, in part to internal resistance to change, and in part to the high cost and risk of the requisite R&D. Another cross-cutting barrier is the lack of good, reliable, low-cost, real-time sensors that can be used to monitor and directly or indirectly control the quality and microstructural properties of intermediate and final products.

Casting Research Needs

Casting-related research that is needed to overcome these barriers can be organized under six major categories (Exhibit 3-4, with the highest priority needs boldfaced):

- Sensors
- Safety
- New Products
- Process Fundamentals
- New Manufacturing Concepts
- Energy

Understanding process fundamentals is perhaps the most important area of research for improving casting methods. A basic, fundamental understanding of the mechanics of metal melting, solidification, cracking, and so on, would provide the basis for the development of technologies to improve process control and product quality.

At present, this type of knowledge is limited, or is not shared among industry researchers and so is of limited value to the industry as a whole. One of the highest research priorities is to develop fundamental information on the solidification of alloys in order to better predict microstructure, surface properties, and the relationship

of stresses and strains at elevated temperatures. Two related research needs include: 1) a fundamental study of

Exhibit 3-4. Major Research Needs of Aluminum Casting Processes (Highest Priority Needs Boldfaced)					
Sensors	Safety	New Products	Process Fundamentals	New Manufacturing Concepts	Energy
<p>Low-cost inclusion meter</p> <ul style="list-style-type: none"> - 100% metal inspection - <10 micron limit - In line - Real time - Operator friendly - Continuous <p>Non-contact sensors to use in direct chill casting that measure shell thickness and surface temperature</p> <ul style="list-style-type: none"> - 1000 - 1200°F - 1/10 mm - 1/8" - Improve productivity and safety <p>Develop a non-contact sensor and method to identify and separate scrap</p> <ul style="list-style-type: none"> - Sensor plus process 	<p>Understand mechanisms causing Al- water explosions</p> <p>Detector for moisture & nonmetallic impurities in charge to furnace</p> <ul style="list-style-type: none"> - Prevent explosions (e.g., phosphates, nitrates) <p>Research to develop cavity-free sows</p>	<p>Develop new secondary alloys</p> <ul style="list-style-type: none"> - Better match scrap to specifications for increased utilization and enhance alloy characteristics based on current alloy technology 	<p>Fundamental information on solidification of alloys to predict microstructure surface properties and stresses and strains</p> <ul style="list-style-type: none"> - Computer model capable of process control in real time <p>Fundamental study of intermetallic phase formation as a function of alloy chemistry and cooling conditions</p> <p>More fundamental research on macrosegregation</p> <p>Form a cooperative continuous casting consortium</p> <ul style="list-style-type: none"> - Expand manufacturing capability <p>Understand oxidation prevention mechanisms</p> <ul style="list-style-type: none"> - Substitutes for Be (non-toxic, non-carcinogenic) <p>More R&D on understanding filtration mechanisms</p> <ul style="list-style-type: none"> - Increase efficiency and lower costs - Increase reliability 	<p>Develop an ingot plant for the future</p> <ul style="list-style-type: none"> - On demand - Energy efficient - High quality product - Zero waste <p>Optimize vacuum or inert gas to prevent oxidation</p> <p>Develop continuous microscalping</p> <p>Develop low -cost process for alloy/scrap purification/upgrade</p> <ul style="list-style-type: none"> - Produce good quality metal from mixed scrap <p>Develop means for removing specific impurities from the melt (e.g., Mg, Fe, Pb, Li, Si, Ti)</p> <p>Continuous high-productivity, thin strip casting process</p> <ul style="list-style-type: none"> - Hot band equivalent gauge <p>Develop a use for nonmetallic products</p> <ul style="list-style-type: none"> - To avoid landfilling & turn wastes into feedstocks <p>Develop university and industry consortium to examine integrated production system</p> <ul style="list-style-type: none"> - Systems level - Total process <p>Develop processes to better separate metal from dross/salt cake</p>	<p>Modification of furnaces to improve fuel efficiency and reduce NOx emissions</p> <p>Develop industry guidelines manual on how to prevent melt loss</p> <p>Develop a high-capacity "furnace" design for the future</p> <ul style="list-style-type: none"> - Safe and environmentally benign - Minimize melt loss - Improve melt rates - Fuel efficient - Cost effective

intermetallic phase formation as a function of alloy chemistry and cooling conditions; and 2) fundamental research on macrosegregation. One of the ultimate goals of such research would be the development of a computer model that is capable of process control in real-time.

Another high-priority in the area of process fundamentals is the creation of a cooperative continuous casting consortium. This consortium would conduct generic, precompetitive research of benefit to the industry as a whole. By creating and pursuing common goals in a cooperative fashion, duplicate efforts could be avoided and expertise held by different companies could be shared and pooled. Such a consortium could also enable the “systems-level” thinking that is currently lacking. The consortium could be established as a “center of excellence” at a university or at a separate location. The consortium would include researchers from industry, suppliers, customers, universities, and national labs. Information developed through cooperative research would be shared. User facilities could be established that could be accessed by individual companies for proprietary research. Other R&D needs in process fundamentals include developing a better understanding of oxidation prevention mechanisms (including the development of nontoxic, non-carcinogenic substitutes for beryllium), and the development of lower-cost, reliable filtration mechanisms (to include not just rigid media, but also technologies such as electromagnetic devices, etc.)

Many research needs are considered “new manufacturing concepts.” These include research that will result in fundamental changes to current manufacturing practices or processes. The highest priority in this area is to develop technologies for removing specific impurities from the melt. Elements of particular interest for removal are magnesium, iron, lead, lithium, silicon, and titanium. Another high-priority is to develop a non-contact sensor and method for identifying and separating scrap materials. This requires sensors that can identify the alloys in the scrap and better processes for physically separating different types of scrap in the plant.

A long-term R&D priority is to develop the ingot plant of the future. This plant should produce high quality metal on demand tailored to the customer’s needs, be energy efficient, and have zero waste. This plant should be designed from a “blank page,” and its design would probably be highly company/location-specific. Other important needs include the development of a low-cost process for alloy/scrap purification/upgrade and the development of processes to better separate metal from dross/salt cake. Finally, there is an important need to find a productive use for nonmetallic products. While the long term goal is to eliminate the creation of dross and salt cake entirely, there is a need in the mid-term to find ways to better separate and make use of these waste materials. This could provide a way to turn wastes into saleable or tradeable resources, avoid landfill costs, and preclude environmental problems.

Sensor research is needed to improve both the quality and structure of cast metal. Sensors that improve quality will aid in detecting and removing impurities and inclusions. Sensors that monitor structure (such as x-ray) can provide information on the metal’s microstructure and uniformity, which would be especially useful in continuous casting applications. The development of a low-cost inclusion sensor is considered a high priority that would help to develop a better understanding of the mechanics of filtration and improve process control and product quality.

In the safety area, research is needed to develop ways to prevent aluminum-water explosions. First, fundamental research is required to develop a better understanding of the mechanisms that cause these explosions, including the triggers that initiate high energy reactions, the necessary conditions, and how surface coatings prevent explosions. Second, sensors that can detect the presence of moisture and nonmetallic contaminants (especially phosphates and nitrates) in the charge to the furnace may help prevent dangerous mixtures from reaching the furnace.

The development of a high-capacity furnace design for the future is one of the highest priority R&D needs that can reduce energy use, improve environmental performance, and lower costs. This furnace-of-the-future may not resemble the melting furnaces used today. Key requirements of this new system are that it be safe and environmentally benign, minimize melt loss, improve melt rates, and be fuel efficient and cost effective. Another important need is the modification of existing furnaces to improve fuel efficiency and reduce NOx emissions. Current melting furnaces are extraordinarily energy inefficient and could be made more efficient through modifications.

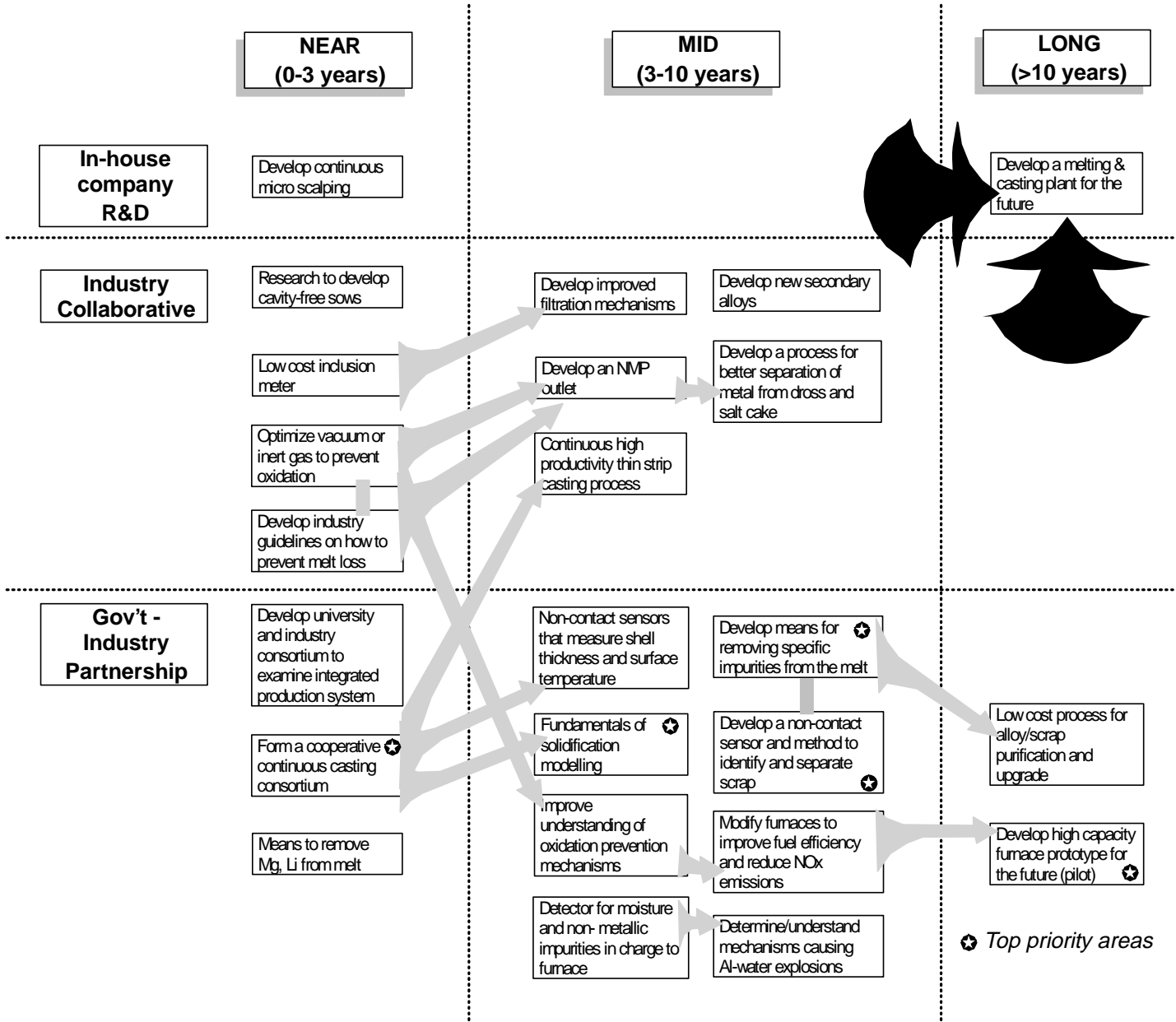
One research need that is not strictly in the casting area is the development of new secondary alloys. Listed under “New Products” in Exhibit 3-4, new secondary alloys would better match the composition of scrap materials with the alloys’ specifications. This would result in increased useability and utilization of scrap materials and perhaps preclude the need to remove impurities whose presence may not degrade the characteristics of the final product. For example, it may be possible to develop new automotive and aerospace alloys that could tolerate higher levels of impurities such as copper and/or magnesium without deteriorating performance. There is a need to re-examine the chemical limits for the alloys and either modify them or develop new alloys that will have the desired mechanical properties but which can be produced for a lower cost.

The R&D needs have been grouped according to the time frame in which R&D results could be expected and identified the organization or group most likely to fund the research (Exhibit 3-5). They also established linkages among the R&D needs. Only two of the needs shown in Exhibit 3-5 are likely to be funded solely by in-house, company R&D funds. These are the development of continuous microscalping (which is likely to be unique to specific products and processes) and the development of the ingot plant of the future. Almost all of the R&D needs would contribute to the development of the ingot plant of the future, as indicated by the bracket shown in Exhibit 3-5. But this “blank page” plant would likely be different for each company, with proprietary processes, technologies, and products, and thus would not be developed using collaborative or government funded R&D.

Linkages among the R&D needs identified for funding by industry collaboratives are shown in Exhibit 3-5. One new research need was added to be accomplished in the near term: the development and publication of industry guidelines on how to prevent melt loss. The guidelines would represent the shared knowledge of the aluminum industry. It was suggested that the Aluminum Association organize the development and publication of these guidelines.

Most of the R&D identified will require cost sharing through government-industry partnerships, including the top five R&D needs identified. The cooperative continuous casting consortium was placed in the near-term category to reflect the fact that the *formation* of the consortium can and should be accomplished in the near term. The *research* to be conducted through the consortium, however, would be of longer-term nature. The formation of a cooperative R&D consortium for casting is important and should be aggressively pursued. The linkages drawn from the consortium to three other primary R&D needs indicates that the success of other research efforts could depend on the successful operation of a cooperative research consortia. The majority of the R&D could produce results useable by industry in the mid-term (3-10 years from the start of the research effort). Long-term R&D needs include the development of a high-capacity furnace-of-the-future prototype (pilot unit), and the development of low-cost processes for alloy/scrap purification/upgrade.

Exhibit 3-5. Research Linkages for Casting



ROLLING AND EXTRUSION

Rolling and Extrusion Performance Targets

The performance targets for rolling and extrusion are shown in Exhibit 3-6. The intent of the target that calls for increasing public awareness of the value of aluminum and aluminum products is to provide information to demonstrate aluminum's potential role in rebuilding the nation's infrastructure including bridges and highways. The intent of the target to enhance the institutions and infrastructure that deliver educational services to aluminum industry personnel is to "go beyond the university system" and strengthen other means for improving the skills and capabilities of employees at all levels of the organization. The target to "Increase the reliability of manufacturer operations to 95%" is meant to include all aspects of the entire manufacturing process and is not limited to the operations phase alone.

Rolling and Extrusion Technology Barriers

Exhibit 3-6. Performance Targets for Rolled and Extruded Products

- Reduce weight by 20%+ through non-conventional forming technologies
- Reduce cost of joining technologies (compared to steel)
- Increase reliability of manufacturer operations to 95%
- Reduce energy use and costs associated with extrusion 20-30%
 - Model extrusion metal flow process
 - Improve the efficiency of thermal processing
- Improve process control
 - Better models of plant operations
 - Temperature analysis sensors for rolling operations
 - Real-time measurement of molten metal composition
 - Pressure sensor for container/die
 - Improve systems design
- Improve productivity and quality of extrusions
 - Lower die cost
 - Thinner wall tolerances
 - Higher speed
 - Expand extrusion die technology

Technology barriers affecting the rolling and extrusion of aluminum can be classified under eight key areas: computer models, process consistency and control, product design, measurement and sensors, manufacturing, alloy characterization, education and training, and non-technical issues (Exhibit 3-7).

Among the most important technical barriers are a lack of computer models and computational algorithms. In many cases a detailed understanding of the production process is missing, both at macro and micro levels. An important caveat is that it may not be possible to create computer tools that can be generically applied. The most useful models may be plant specific.

Several non-technical barriers are also believed to be highly important. One is a perceived lack of understanding by many in the aluminum industry about the cost and performance details of competing materials. To correct this, R&D efforts should focus on finding ways for semifabricated aluminum products to be more competitive (on both a cost and performance basis) with products made of steel, glass, plastic, concrete, or other materials that are used by customers for the same or similar purposes.

Another non-technical barrier is the perceived difficulty of convincing business leaders in the aluminum industry to invest in significant changes to existing fabrication processes. Retooling, redesigning, and re-engineering may require significant new investment and may not receive the support of senior management,

even when justified from a technical point of view. Good ideas may be left on the drawing board because the costs or perceived risks are believed to be too high.

Exhibit 3-6. Technology Barriers in Rolling and Extrusion					
Computer Models		Process Consistency and Control	Product Design	Measurement and Sensors	Manufacturing
<p>Lack of models that can accurately simulate production processes</p> <ul style="list-style-type: none"> - Ability to create such models that can be generically applied to more than one plant <p>Lack of integrated process models that are capable of fully incorporating sub-components</p> <p>The extrusion process is not being optimized</p> <p>Insufficient understanding of aluminum rheology</p> <p>Lack of a modeling process to get to the end-product</p> <p>Lack of constitutive models that are also capable of addressing alloy chemistry</p>	<p>Available materials models are not sensitive to real performance differences</p> <p>Lack of well-recognized cost-modeling processes</p> <p>Lack of effective optimization models</p> <p>Lack of models that have the capability of relating structural properties to manufacturing processes and the materials employed</p> <p>Lack of life-cycle design methodologies</p> <p>Lack of detailed models that can describe the key relationships between end-products and raw materials</p>	<p>General failure to achieve a "real" iso-thermal extrusion process</p> <p>Need to eliminate post deformation heat treatments</p> <p>The knowledge of surfaces is much less than the knowledge of bulk product</p> <p>Aluminum products lack of dimensional stability</p> <p>The machinability of steel dies is limited</p>	<p>Lack of useful design models for the end-product</p> <p>Limited ability to fully customize products</p> <p>Limited understanding the performance of aluminum products over long-term use (10-15 years)</p>	<p>Lack of sensors to measure microstructure changes on-line</p> <p>Limited ability to get accurate temperature measurements at the point-of-process</p> <p>Machinability tests are ineffective</p>	<p>Lack of tested way to design and implement tooling that works properly the first time</p> <p>Concerns about recycling mixed scrap</p> <p>Limited effectiveness of joining technologies</p> <p>Corrosion problems between aluminum and other materials</p> <p>Limited capability to produce extrusions of varying cross sections</p> <p>Lack of techniques for the inspection of joining technologies</p> <p>Prohibitively high costs of surface technologies</p> <p>Environmental emissions</p> <p>Damaging effects of oxides on joint efficiency</p> <p>Lack of effective techniques for curing paint at low temperatures</p>

Exhibit 3-6. Technology Barriers in Rolling and Extrusion (continued)		
Alloy Characterization	Education and Training	Non-Technical Issues
<p>Lack of methods to measure surface quality and relate it to the history of the material</p> <p>Current tool/die steels and their material development do not satisfy industry needs</p> <p>Lack of understanding of the metal structure as related to the prior thermal history of the alloy</p> <p>There is a need for alloys whose design permits increases in modulus compared to conventional alloys</p> <p>Aluminum has the tendency to adhere to surfaces when hot</p> <p>The formability of aluminum sheet is limited compared to most other base metals</p>	<p>There is a general lack of understanding of the cost and performance attributes of competitive materials</p> <p>Customers place a high priority on first cost and less on longer term benefits</p> <p>There is a critical gap in the number and training of metallurgical engineers</p> <p>Workers need more effective training on safety issues to produce real behavioral changes</p> <p>There is insufficient employee training to build skills</p> <p>The technology transfer process is generally inefficient</p>	<p>Significant investments in existing technology assets may act as an impediment to new technologies investment, particularly when these technologies will require major new capital expenditures</p> <p>There is resistance to making paradigm shifts in manufacturing processes</p> <p>The antitrust environment can have a "chilling" effect on technology advancement</p> <p>Existing building codes and standards don't properly account for the properties and advantages of aluminum products</p>

Rolling and Extrusion Research Needs

Research to overcome technology barriers should proceed along several related R&D pathways. Key research areas for rolling and extrusion include development of:

- improved alloys and tool/die materials,
- advanced extrusion technologies,
- advanced sheet technologies,
- advanced manufacturing processes,
- computer models,
- advanced sensors,
- advanced research on new technologies,
- management analysis tools and techniques, and
- education and training.

Specific research needs under these areas are listed in Exhibit 3-7, with the highest priority needs boldfaced. Over half of the 58 identified research needs are considered to be priority requirements.

Some of the most important research needs involve advanced sheet and extrusion technologies. Formability of aluminum sheet could benefit from further research and the development of more advanced technologies in both hot and cold rolling processes. Extruded products would benefit greatly from more wear-resistant die materials, computerized die designs, and more advanced techniques for handling metal flow in hollow extrusion dies.

**Exhibit 3-7. Major Research Needs of Rolling and Extrusion
(Highest Priority Needs Boldfaced)**

Improved Alloys		Advanced Extrusion Technologies	Advanced Sheet Technologies	Advanced Manufacturing Processes	Computer Models
Develop improved mathematical or computational tools for understanding the linkages across physical size scales to better represent the impacts of the material's chemistry and thermo-mechanical processing on alloy microstructure	Develop corrosive-resistant architectural alloys Develop better understanding of the role of kinetics in metal microstructure Develop foamed aluminum Develop tool/die steel processing technologies (cast and powder metallurgy) to improve cooling performance	Develop computerized extrusion die designs Produce top quality extruded products using less energy Develop better understanding of the factors affecting metal flow in hollow extrusion dies Develop computational tools to describe the relationship of point location to the centroid of the billet and its impact on extrusion pressure	Develop more complete understanding of the relative strength and formability of alloys as a function of hot rolling, structure, cold rolling, reduction sequence, and thermal history Develop techniques to determine sheet formability characteristics and associated test methods Enhance the surface quality in strip and slab cast alloys	Research the relationship between constitutional instability and: structure, property, process Develop techniques to manufacture net shapes without any intermediate processes Evaluate micro-structure development under specific extrusion conditions Increase extrusion speed while maintaining surface quality More completely understand crystallographic texture changes Better understand and control micro-structure gradients Perform studies on reproducibility in manufacturing Pursue quench-path modeling for microstructure to predict toughness and strength Develop methods to produce aluminum shapes with inherent surface finish Develop more complete understanding on the effects of time (process research) on the changing properties of materials	Develop process engineering models that can be used for process control Develop methods for optimizing the sequence of processes in manufacturing systems Determine the state-of-the-art in modeling aluminum rheology Develop software capable of handling three-dimensional solids models Develop metal flow analysis software
Complete formability studies of strain, strain rate, and temperature on the state of stress	Develop alloys to provide higher modulus alloys Develop a single alloy for recyclability Further develop extrusion alloys to overcome the restrictions of the extrusion-limit diagram Develop better understanding of measurement of grain boundary characteristics	Develop tool/die configurations for variable extrusions Develop cooling practices in extrusion that eliminate shape and dimension distortions Develop continuous extrusion technologies beyond concast/conform processes Develop improved extrusion alloys that possess the base characteristics of 6063 and that have ten times the manufacturing potential and productivity	Develop strip/slab casting technologies and methods for surface, texture, and segregation Develop uniform microstructure in thick plate Develop uni-alloys for bodies and ends in the can industry		
Develop more complete understanding of the beta and beta prime transformations of the 6000 series alloys					
Conduct fundamental science and engineering work on the machinability of aluminum alloys					
Acquire a more complete understanding of metastable phase transformation kinetics					
Develop alloys that are the equivalent or better in cost and performance to competing materials					

Exhibit 3-7. Major Research Needs of Rolling and Extrusion (continued)			
Advanced Sensors	Advanced Research in New Technologies	Advanced Management Analysis Tools and Techniques	Education and Training
<p>Develop visual inspection devices for high-speed manufacturing capable of operating in industrial environments</p> <p>Develop non-contact temperature, speed, and pressure sensors</p> <p>Develop high temperature sensors for phase transformation and process control</p>	<p>Research methods that can eliminate processing steps currently needed to produce end products</p> <p>Research aluminum alloys that have the same properties as steel (e.g., that can operate in a metal stamping plant equivalent to steel)</p> <p>Research techniques for achieving satisfactory welding without extensive surface preparation</p>	<p>Enhance methods to understand customer requirements and the technical steps to achieve them</p> <p>Analyze different manufacturing process for optimized product applications</p> <p>Develop life-cycle costing algorithms capable of gaining broad acceptance</p> <p>Develop initiatives and participate in the development of new construction standards for bridges, highways, and related infrastructural improvements</p> <p>Conduct market analyses to determine the potential of amorphous aluminum alloys</p>	<p>Train more metallurgical engineers</p> <p>More effectively train industry personnel at all levels to enhance skills and effectiveness</p>

The development of improved aluminum alloys is another important area requiring further research and technology development. More fundamental scientific and engineering information on the microstructure of materials could be of great value in developing and handling new aluminum alloys. Properties such as formability and machinability are important characteristics for the new alloys to have, but some advances in basic science and engineering are needed to get there.

Another important area is in the development of advanced manufacturing processes. Research in this area must address new ways to produce extruded or rolled aluminum products at less cost and with equal or higher quality. Virtual manufacturing computer simulations may offer an opportunity to view new concepts in manufacturing processes.

Research and development in sensors, computer models, and management analysis tools are also very important. The highest priorities in these areas include developing ways to better understand customers, their product requirements, and the technical means of meeting customer demands. Exhibit 3-8 provides a list of the research needs organized by the likely source of funding and the time frame (near-, mid-, and long-term) in which results could be expected to be achieved. The research needs listed are the priority activities from Exhibit 3-7.

Seven of the research needs shown in Exhibit 3-8 are well-suited for in-house funding. The ideas in this category are more plant- specific and less likely to lead to solutions that are generally applicable.

Exhibit 3-8 also shows five major linkages among the priority research needs:

Formability for Rolling and Extrusion. Formability is a major theme underlying several of the research needs. This theme includes research needs from the advanced sheet, extrusion, alloys, and manufacturing

processes categories and involves funding from in-house, industry collaboration, and government partnership sources.

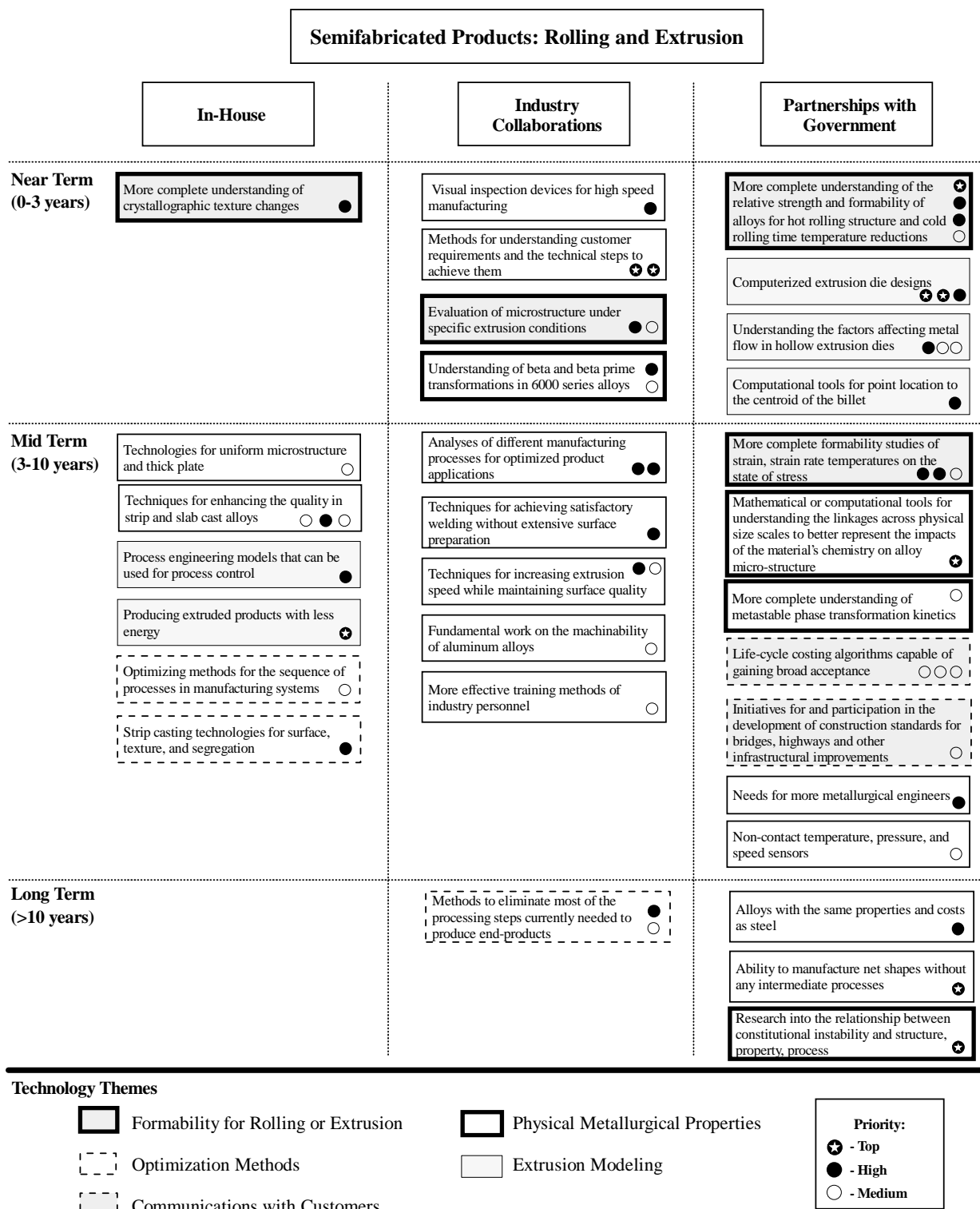


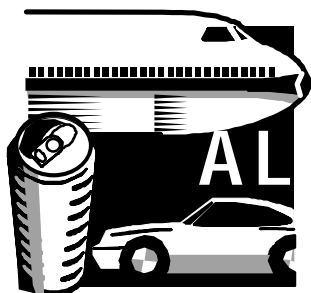
Exhibit 3-8. Funding Source and R&D Time Frame for Rolling and Extrusion Priority Research Needs

Physical Metallurgical Properties. A second major theme covers the more fundamental research needs in metallurgical engineering and materials sciences. These ideas tended to be in the mid- and long-term categories with funding primarily from industry collaborations or government partnerships.

Optimization Techniques. A third theme is in the area of computer algorithms or other tools for making the manufacturing process more efficient. The area involves developing a better understanding of process steps and finding ways to optimize process sequencing or eliminating process steps entirely.

Extrusion Modeling. A fourth theme involves developing computer tools to improve the extrusion process. This theme includes research in the near-, mid-, and long-term time frames with funding potentially coming from all three sources.

Communications with Customers. A fifth theme falls in a non-technical area. It includes the need for life-cycle costing tools that have broad acceptance, and the need for the industry to take a more active role in developing new construction standards for bridges, highways, and other infrastructural improvements.



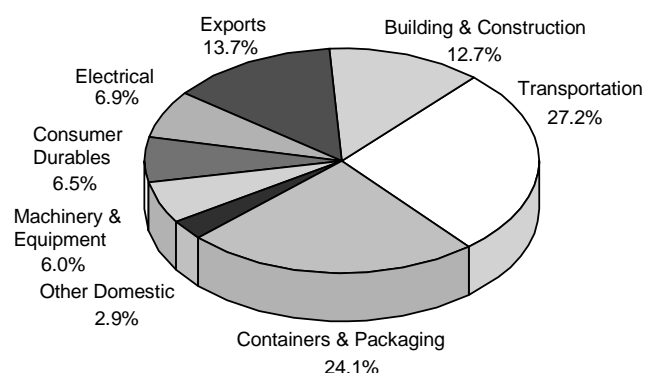
4 Finished Products Sector

The Finished Products Sector covers the application of aluminum materials and components in finished end products.

Current Situation

Finished aluminum products are important in several key markets. Major current and emerging markets for aluminum include packaging, transportation, building and construction, and national infrastructure. Exhibit 4-1 shows the distribution of aluminum net shipments by major market.

The transportation sector continues as the largest market for aluminum, representing 27.2% of total domestic shipments in 1995. Included in this market are passenger cars, trucks and buses, and trailers and semi-trailers. At 24.1% of total domestic shipments, the containers and packaging industry is the second largest market for aluminum. Representative products include metal cans, semi-rigid food containers, and household and institutional foils. The buildings and construction market accounted for 12.7% of total shipments in 1995. This market includes residential, industrial, commercial, farm, and highway applications as well as mobile homes.



Source: The Aluminum Association, Inc.

Other significant markets include:

- electrical (ACSR and insulated wire and cable products),
- consumer durables (large appliances and air conditioning equipment),
- non-electrical machinery and equipment (agricultural, construction and industrial machinery, irrigation pipe, ladders, fasteners, etc.)

Trends and Drivers

Government Regulations and Public Policy

As with the primary products and semifabricated sectors, government regulations and public policy have a significant effect on the finished products sector. In recent years, concern for the

Exhibit 4-1. Distribution of Aluminum Net Shipments by Major Market

environment has stimulated a strong interest in expanded use of aluminum by the automotive industry. In particular, rising U.S. Corporate Average Fuel Economy

(CAFE) standards and public concern about global warming have initiated activity to reduce vehicle weight. Since energy consumption is directly related to weight, automobile companies have sought to reduce weight by increasing the use of lightweight materials, including aluminum sheet, extrusions, castings, and forgings.

The federal government's role in regulating the energy and environmental performance of industries will continue to evolve, particularly in the area of ecological sustainability. There will likely be an emphasis on processes, products, and technologies that address these concerns in the aluminum industry and among its customers.

Market Trends

Throughout its history, aluminum's growth has been as a replacement for existing structural materials. During the past decade, aluminum shipments to the U.S. container and easy-open end market grew at more than double the rate of aluminum shipments in aggregate. The growth of aluminum consumption in the U.S. packaging industry is slowing, and domestic can sheet producers are increasingly looking to offshore packaging markets to provide growth opportunities. In addition, new opportunities are arising from the application of advanced fabrication technology that can produce an aluminum beverage can that competes with varied forms of plastic and glass bottles. The total value of aluminum to the economic and social values of the U.S. economy is now, and will continue to remain, strong.

Over the past 35 years, aluminum has also gradually penetrated the production of selected auto parts, where its cost per pound can be justified on the basis of weight reduction or performance. From about 100 pounds per car on average in 1960, the average passenger car currently contains about 250 pounds of aluminum per car. While carbon and specialty steels continue to be the dominant materials used in the manufacture of automobiles, aluminum could eventually replace a significant portion of this steel content. To date, castings account for more than two-thirds of current aluminum use in automobiles; the greatest potential for additional savings is with substitutions in body structure by aluminum sheet and extruded products. Industry/government partnerships, such as the USCAR/USAMP programs, are already in place in this market segment. By the year 2020, the aluminum content of the average passenger vehicle could be as high as 700 pounds.

In the construction market aluminum has become an essential material, providing durability and strength to commercial and residential buildings. An emerging construction trend is the use of aluminum in key portions of the nation's infrastructure such as bridges, electrical transmission lines, waste treatment facilities, and oil rigs. Although construction levels have been relatively constant for a number of years, there are growing opportunities to replace aging bridges with aluminum decks and/or girders without rebuilding the foundations and piers. This could generate a significant market for aluminum plate and extrusions, as an estimated 50,000 concrete and steel-reinforced bridges in the United States are due for rebuilding in the next ten years (AA 1996a). Aluminum allows state and local agencies to increase the life of existing bridges, saving billions of dollars by replacing and upgrading their deck systems.

Other likely areas of growth that interface both the transportation and infrastructure markets include high-speed ferry and ocean cargo ships and high-speed trains. Aluminum will also continue to be an important component of aircraft structures for both military and commercial transportation. However, aluminum

shipments for military applications have been substantially reduced because of recent changes in the world's geopolitical environment, including the breakup of the USSR.

Competition

Customer industries will require increasingly sophisticated materials to meet demanding engineering specifications. While market opportunities are promising, aluminum continues to compete with materials that may offer even lower cost, higher strength, lighter weight, or some other competitive advantage. Advances in engineered materials, alloys, end product manufacturing technologies, and product design technologies will help to meet customer requirements. Expanded use of aluminum in these markets requires that material property issues be addressed to reduce the cost and improve the performance of aluminum in specific applications. The technical challenges involved may be too complex for companies to overcome alone. Collaborations, in the form of partnerships, consortia, and joint ventures, could play an increasingly important role in assuring the continued health of the industry.

Global partnerships and consortia may provide U.S.-based companies opportunities to position themselves within new markets and to face new competitors. International joint ventures are likely to become much more common as cost/risk-sharing mechanisms in the industry. Access to critical new markets, world-class operating technologies, and capital resources will become increasingly important strategic objectives. Scientific and engineering capability will become critical factors for U.S. materials producers attempting to develop these types of partnerships.

Performance Targets

The industry-wide performance targets that focus on increasing aluminum use in specific end-product markets are shown in Exhibit

4-2. In addition, targets to reduce the cost of aluminum through improved processing and production techniques can also greatly affect the acceptance of aluminum products in key markets.

Specific performance targets for the finished product sector are given in Exhibit 4-3. For many targets, the expected time for completion and the penetration rate could not be readily quantified, although numerical targets can be estimated with additional market information. Markets and products for which aluminum could play an expanded role include food cans, autos and light trucks, marine applications, transportation structures (such as lightweight bridges), desalinization equipment, housing, high-rises, scaffolding, lightweight construction tools, mass transit vehicles, aerospace, and military applications.

Exhibit 4-2. Key Industry-Wide Performance Targets Affecting the Finished Products Sector

1. Reduce the costs associated with metal production by 25%.
2. Reduce the cost ratio of aluminum-to-steel to less than 3-to-1 for auto applications.
3. Increase aluminum use in auto markets by 40% in 5 years.
4. Increase aluminum use in non-auto transportation markets.
5. Increase aluminum use in infrastructure markets by 50%.
6. Increase aluminum use in building and construction markets.

Technology Barriers

Several key technology barriers inhibit greater utilization of aluminum in finished products. Some barriers concern finished product design and engineering and the customer's knowledge of the performance characteristics of aluminum materials. Other barriers derive from insufficient fundamental understanding

Exhibit 4-3. Performance Targets for the Finished Products Sector

- Expand market applications using advanced design-by-analysis technology.
- Improve competitiveness of aluminum packaging compared to PET and other key polymers.
- Make aluminum more friendly to food cans.
 - Coating system for food and beverages.
 - Lower number of specifications in food can market
- Extend life and improve the performance of aluminum products.
- Develop improved and new materials and alloys.
- Reduce costs through computer-assisted material design.
- Reduce energy use in the transportation sector through innovative use of aluminum.
- Devise aluminum-containing composite materials with unique properties.
- Increase customer knowledge base for aluminum finished product design and manufacturing.
- Reduce the cost of aluminum relative to other materials.
 - Decrease fabrication costs for finished products.
- Penetrate new markets and expand applications for aluminum products.
 - Develop and deploy new aluminum bridges/bridge decks, including structures with less than 20 lbs/sq. ft.
 - Expand the use of aluminum in houses, high-rises, and scaffolding
 - Develop marine applications
 - Lightweight, heavy-duty tools for construction.
 - Advanced aluminum structures for transportation uses.
 - Develop basis for cost-effective aluminum desalination equipment.
 - Conduct market analysis to choose areas
- Educate students and develop a national scientific network.
- Integrate product, process, and material design..
- Educate engineers and researchers to fully understand aluminum and its properties.
- Aluminum sheets vs. steel rolls, surface quality.
- Standardize sheet making tech./operations to increase involvement of suppliers.
- Enhance aluminum product differentiation
 - Optimize strength, formability, earring

of the structural properties of aluminum and how they relate to processing, design, and products. Categories of finished product barriers include aluminum properties and characterization, in-process technologies, enabling technologies (to help put aluminum into an end-use), customer knowledge-base (to increase understanding of aluminum properties to improve product design), computational barriers, and non-technical barriers (Exhibit 4-4).

Aluminum property issues include obtaining desirable corrosion properties (e.g., how do you get a 20-year corrosion test simulated in a short time with some degree of conviction), getting a higher modulus with lower density at reasonable cost, and complex properties and characteristics related to crystallographic textures and how that affects formability. While the end-market drives technology needs in finished products, advances are often

constrained by upstream limitations in process technologies and a lack of understanding of the basic property, composition, and processing interrelationships.

Processing technology barriers include the need for better process controls (including a lack of adequate sensor capabilities), the long and involved process to roll ingot into sheet, advanced material synthesis and forming processes, continuous processing technologies to obtain higher yields, and recycling and segregation equipment to achieve higher recycling rates in an economically viable manner. In addition, the large amounts of energy needed to extract aluminum is a key barrier that affects the cost of aluminum and its use in end products.

Many of the barriers to the greater use of aluminum in end products can be found in how the customer or end producer engineers and manufactures the final product. These barriers may be found in many of the end-use product areas such as construction and infrastructure, packaging, automotive, and non-automotive transportation (including high-speed ships, trains, and planes). Customer/enabling technology barriers included formability and

Exhibit 4-4. Technology Barriers in the Finished Product Sector					
Aluminum Properties	Processing Technologies	Enabling Technologies	Customer Knowledge Base	Computational Barriers	Non-Technical Barriers
Corrosion performance	Need better process control technology	Lack of formability	Lack of customer and supplier relationships and involvement	Analytical and numerical methods are not good enough for analysis and design of product	Lack of generic multi-purpose alloys and process technology to increase market participation
Surface durability and hardness	- Lack of adequate sensors	- Difficult to attain high formability and strength of sheet			
Enhanced modulus of elasticity	Sheet rolling process is long and involved	Better methods for faster, cheaper joining and superior coating	Not enough demonstration products or prototypes to test	Inadequate computer design tools	Lack of educated engineers and workers
Thermal conductivity of aluminum is high -- tendency to alloy with welding electrodes	Lack of advanced material synthesis process	Unconventional near-net shape technology	Insufficient performance database and design codes	- Simulation and design	Customers biased by experience in the use of competing materials--
Not enough basic research on composites and hybrid metal in metal	Need better process from melting to final product - continuous processing	Enhanced lubricating systems	Unrealistically conservative design codes	Computational material science	customer industry infrastructure not comfortable in using aluminum
Crystallographic textures - aluminum exhibits zero strain rate hardening	Improve recycling and segregation equipment and techniques for higher recycling rate	Material joining tech development - Dissimilar materials			Lack of sufficient R&D funds
Limited understanding of relationships between microstructure and material performance	Aluminum is energy intensive and costly to extract	Lack of integration between product process and product design			Lack of coordination between industry, academia, and government
		Better accelerated tests for long-life performance			

strength issues of sheet; the need for faster, cheaper joining methods and better coatings; requirements for enhanced lubricating systems; difficulties in joining dissimilar materials; the limited formability of aluminum compared to steel; and demonstrating long-life performance. One barrier of special interest was the lack of integration between process and product design.

In addition to enabling technology barriers, many customers are not very sophisticated in their knowledge of the characteristics and design properties of aluminum. For example, some designers substitute aluminum for steel in products to take advantage of its lightweight properties but they do not alter the product design to take full advantage of other beneficial properties. This can lead to unrealistically conservative design codes that can contribute to aluminum's cost disadvantage. Factors that contribute to this lack of knowledge include insufficient performance databases, insufficient demonstration products or prototypes to test, and lack of a strong customer-supplier relationship.

Computational barriers, which apply to several technology areas, include analytical and numerical methods that are not good enough for adequate analysis and design of products, and inadequate computer design tools, particularly for simulation and design.

New design concepts, such as double-walled unconventional fuselages and innovative high performance ship, truck, and rail structures, need to be explored.

Several non-technical issues also appear to contribute to the limited adoption of aluminum by finished products producers. Barriers included a lack of educated engineers and workers, lack of sufficient R&D funding, and insufficient cooperation between aluminum producers and customers and among government, industry, and academia.

Research Needs

Research that is needed to overcome these barriers appear to be of two types: understanding and solving problems associated with aluminum material properties, and improving technologies that enable end-producers to engineer and manufacture aluminum-based products. The workshop participants did not attempt to identify all of the research needs for specific end-product areas because they had a limited knowledge base of these industries and found that cutting across all of the market areas separately created too many redundancies. Instead, categories that mirrored the barrier areas were used: aluminum properties/fundamental knowledge, processing technologies, finished product (enabling) technologies that help customers adopt and use aluminum more effectively, full-scale experiments to support finished product applications, and standards and policies to facilitate greater use of aluminum by producers (Exhibit 4-5, with the highest priority needs boldfaced).

The most important research need is to fully understand the relationships of aluminum alloy composition and processing and its effect on microstructure and properties that underlie the utilization of aluminum-based materials. This understanding must be gained in order to fully exploit market applications and increase the demand for aluminum products. Component research needs in understanding structure property relationships include improving constituent models for aluminum alloys, improving computational methods for analysis, developing 3000 series alloys for end stock beverage containers, and developing zero-earring, high strength and formability can sheet product. Achieving a full understanding of aluminum properties should be considered as a necessary but insufficient condition to realize full commercial innovation. Subsequent technology development challenges must still be overcome once material property issues are fully addressed. For example, significant technological challenges exist in non-mechanical joining methods, hydroforming technologies, and improved extrusion design.

Within the processing area, research on advanced forming technology for net-shape and near net-shape products is a high priority. This includes semi-solid technology, spray forming, casting, physical vapor deposition, powder metallurgy technology, and rapid solidification. Achieving surface-defect-free

continuous cast sheet for 5000/6000 series alloys is also a high priority research need. Other priority processing technology needs include inexpensive, large volume methods to improve surface hardness; development and application of computational

**Exhibit 4-5. Major Research Needs of the Finished Product Sector
(Highest Priority Needs Boldfaced)**

Aluminum Properties/ Fundamental Knowledge	Processing Technologies		Finished Products Technologies	Full-Scale Experiments to Support Finished Products	Standards/ Policies
<p>Fully understand the relationship of aluminum alloy composition and processing and its effect on microstructure and properties</p> <ul style="list-style-type: none"> - Zero earring, high strength formability can sheet product - Improve constituent models for aluminum alloys - Computational methods for analysis - Develop 3000 series alloys for end stock beverage <p>Surface chemistry of aluminum alloy to understand corrosion and joining issues</p> <p>Develop economically viable aluminum alloys with altered/improved physical properties: higher modulus and reduced density</p> <ul style="list-style-type: none"> - aluminum-magnesium - aluminum-lithium <p>Improve quantitative microstructure characterization techniques</p>	<p>Non-heat treatable automotive alloys and processes</p> <p>Advanced forming and net-shape, and near-net shape technology</p> <ul style="list-style-type: none"> - Semi-solid casting - Casting spray-forming - Spray forming - Physical vapor deposition - PM technology - Rapid solidification <p>Food and beverage can compatible coating</p> <p>Enhanced durability of semi-refractory welding electrode materials</p> <p>Engineered material products (laminated, metal matrix composite)</p> <p>Reduce process waste in aluminum production</p> <p>Semi-solid pre-treated extrusions billet</p> <p>Foamed aluminum assessment</p>	<p>Possibility of alloy separation and/or purification</p> <p>More work on metal composites for auto engines</p> <p>Develop in-line surface inspection systems for hot mill</p> <p>Achieve surface-defect-free continuous cast 5000/6000 sheet</p> <p>Alloys to replace non-recyclable housing on appliances and computers</p> <p>Low cost, large volume methods to improve surface hardness</p> <p>Non-conventional methods to make aluminum-magnesium master alloys</p> <p>Develop low-inclusion process for molten aluminum</p> <p>Develop high performance foam laminate structures that are economical</p> <p>Develop and apply computational methods for process simulation</p>	<p>Eliminate pretreatment for joining</p> <ul style="list-style-type: none"> - Bonding - Spot welding <p>Simulations of finished product fabrication processes including material variability</p> <p>Parametric study of friction-stir welded applications</p> <p>Knowledge base and demonstration products for forming processes</p> <p>Develop integrated numerical methods for analysis and robust design of product, process, and material</p> <p>Improve technology design of extrusion</p> <p>Extend aluminum knowledge base for hydroforming of components</p> <p>Non-mech joining methods for non-weldable alloys</p> <p>Design concepts for use of aluminum in mass transit vehicles</p> <p>Joining methods for high volume multi-product form structures</p> <p>Reduce process waste in finished production</p>	<p>Design/build/test prototype bridges</p> <p>Crash-test prototype vehicles</p> <p>Apply aluminum in earthquake-resistance structures</p> <p>Develop long life skid-resistant surfaces</p> <p>Advanced marine applications</p>	<p>U.S. policy research to help make U.S. industry more globally competitive</p> <p>Promote joint R&D projects academic-industry-government with <u>students</u></p> <p>Consolidate alloys tempers, products, and processes to simplify aluminum manufacturing</p> <ul style="list-style-type: none"> - Develop standard specifications - (e.g., for food cans)

methods for process simulation; non-heat treatable automotive alloys and processes; reduction of process wastes by aluminum producers; and alloy separation and purification.

Research priorities for finished product technologies include developing integrated numerical methods for robust design and analysis of product, process, and material; producing simulations of finished product fabrication processes; developing a knowledge base and related demonstration products for forming processes; eliminating pretreatment for joining methods such as adhesive bonding and spot welding; developing design concepts for the use of aluminum in mass transit vehicles (i.e., trains, buses, and ships); and improving joining methods for high-volume, multi-product form structures.

Efforts are also needed to demonstrate the viability of aluminum-based products for finished product manufacturers. Full-scale experiments are needed in several areas, most importantly in the design, building, and testing of prototype bridges made from aluminum. This is a good example of where aluminum is not going to have significant penetration without heavy participation on the part of the state Departments of Transportation, the Federal Highway Administration, or the end-customer of the bridge. Similar needs include crash testing of prototype vehicles, earthquake-resistance structures, and a long-life skid resistance surfaces as it would apply to a bridge.

Certain policies and standards are also believed to be important requirements. For example, it will be important to pursue much of the identified research through joint R&D projects with academia, industry, and government and to involve university students in this process. Finally, the consolidation of the variety of alloys being used for common purposes, such as food cans, can help to simplify the products and processes that require aluminum and thereby drive down the product cost.

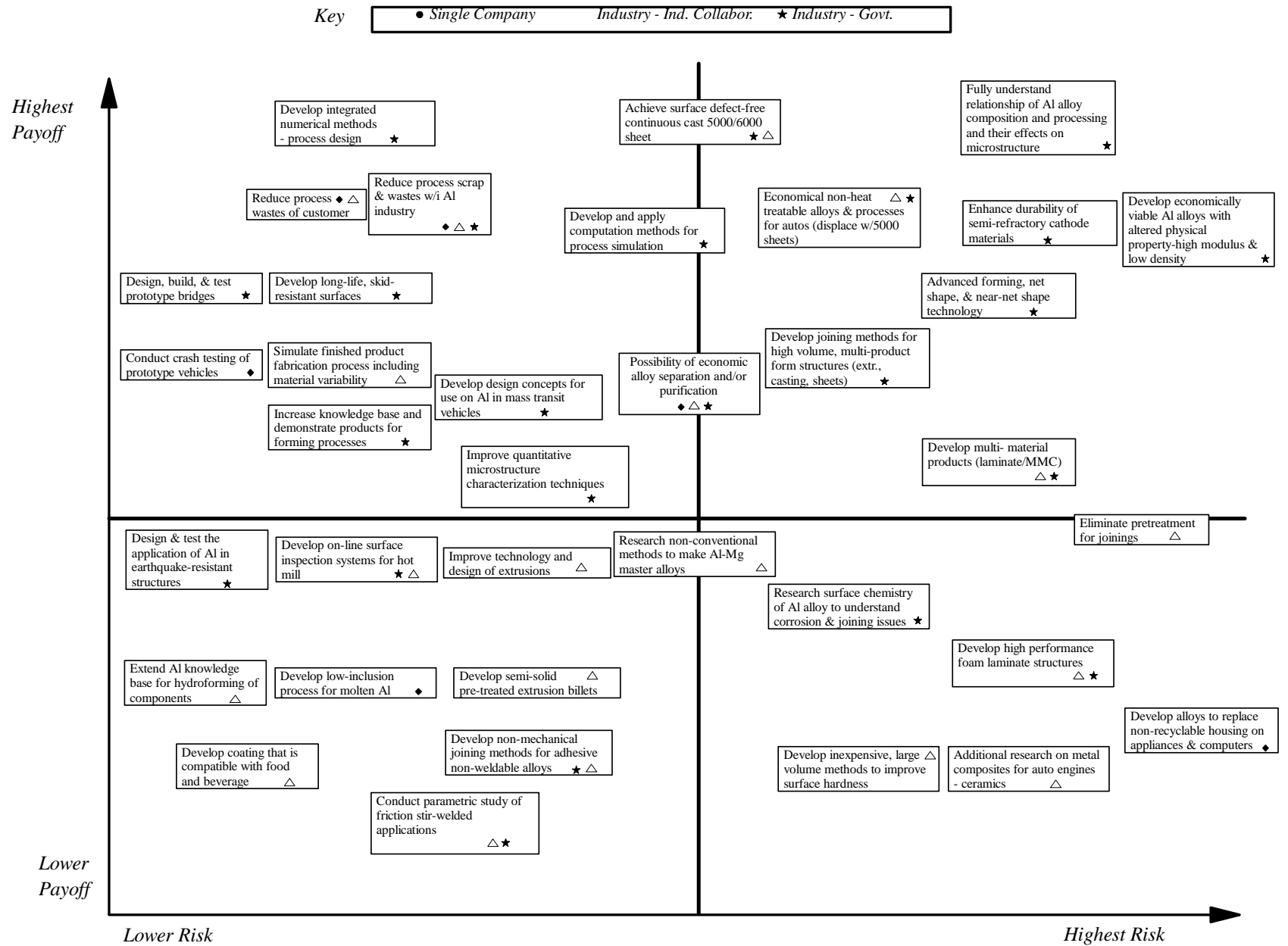
To analyze the research needs, a grid that measured risk along one axis and payoff along the other was constructed. *Risk* was broadly interpreted as the probability that the research would result in a successful outcome. *Payoff* was interpreted as being a measure of both commercial profitability and increased use of aluminum in finished products. Research needs were placed on the grid according to their perceived risk and payoff as shown in Exhibit 4-6.

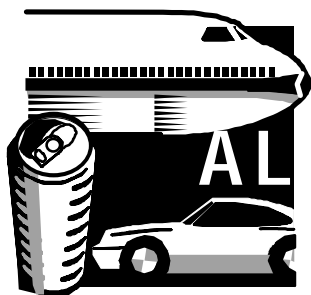
While some research, such as developing coatings that are compatible with food cans, might yield high payoffs for specific industry segments, if the segment represents only a small portion of overall aluminum use, it may be judged to have a smaller overall payoff. In addition, some research areas include a mix of activities that may have high, low, or medium risk. These areas, such as research on the fundamental structure property relationships, were judged on their overall risk and payoff to the industry.

As a final step, the role of potential research funders in supporting each research activity has been assessed. Each research need was analyzed to determine if the research would most likely be pursued by a single company, through industry-industry collaboration (among producers or producers and customers), or through industry-government partnerships. In some cases, a particular research area, such as economic alloy separation and purification, might have component activities that would fall under each funding arrangement.

Research areas that were characterized as higher-risk and higher-payoff were nearly always viewed as requiring an industry-government partnership. Lower payoff research areas, which might only benefit a particular market segment, were generally viewed as requiring industry-industry collaborations or single company research.

Exhibit 4-6. Risk and Payoff of Finished Product Research Needs





5 Summary

Research Integration

An important objective of the roadmap is to understand the relationships and dependencies among research activities. In each of the four sectors, a slightly different approach is used in describing how proposed research activities should be linked within their industry segment (see individual chapters for these results). However, areas of similarities exist between the sectors' results and the interdependencies of research activities. For example, the need to better characterize materials and understand aluminum properties underlies technology advancement in several sectors.

Exhibit 5-1 provides an initial framework for describing some of the cross-cutting research needs for the aluminum industry. Common research themes include fundamental understanding of processes and materials, enabling technologies, improved metal quality, system-level approaches to aluminum production, education of customers and workers, and improving economics through cost reduction. While there was a different focus for each sector of the industry, these themes could be helpful as a basis for organizing research needs.

A Cooperative Effort

While the need for technology investment is considerable, intense competition makes it difficult for U.S. aluminum producers to make the research and technology investments necessary to succeed in global markets. Despite a generally prosperous economy, real R&D spending in the United States has remained relatively flat for several years. Competitive pressures have cut corporate investments in longer-term basic and applied research in favor of near-term product research. At the same time, Federal agencies have experienced eight consecutive years of R&D budget cuts and are ill-equipped to singlehandedly provide the underlying research that aluminum producers will need to compete effectively.

Through the *Aluminum Technology Roadmap Workshop*, the industry successfully developed an initial consensus on priority research needs, as described in this roadmap. The ultimate value of an industry roadmap is its ability to align research across industry, academia, and the Federal sectors. By articulating its technology strategy in this document, the aluminum industry hopes to motivate companies, the academic community, and national laboratories to refocus their research efforts to conform with the needs of the industry.

During the workshop, there was a call to cooperate more within the industry on technical issues. This includes cooperation among companies present at the meeting but also with companies that were not present. In particular, there was strong encouragement to work with customers to better understand end-product needs and material requirements. Many workshop participants supported the idea of consortia within the industry and partnerships with the government as logical and efficient ways to accomplish ambitious research tasks.

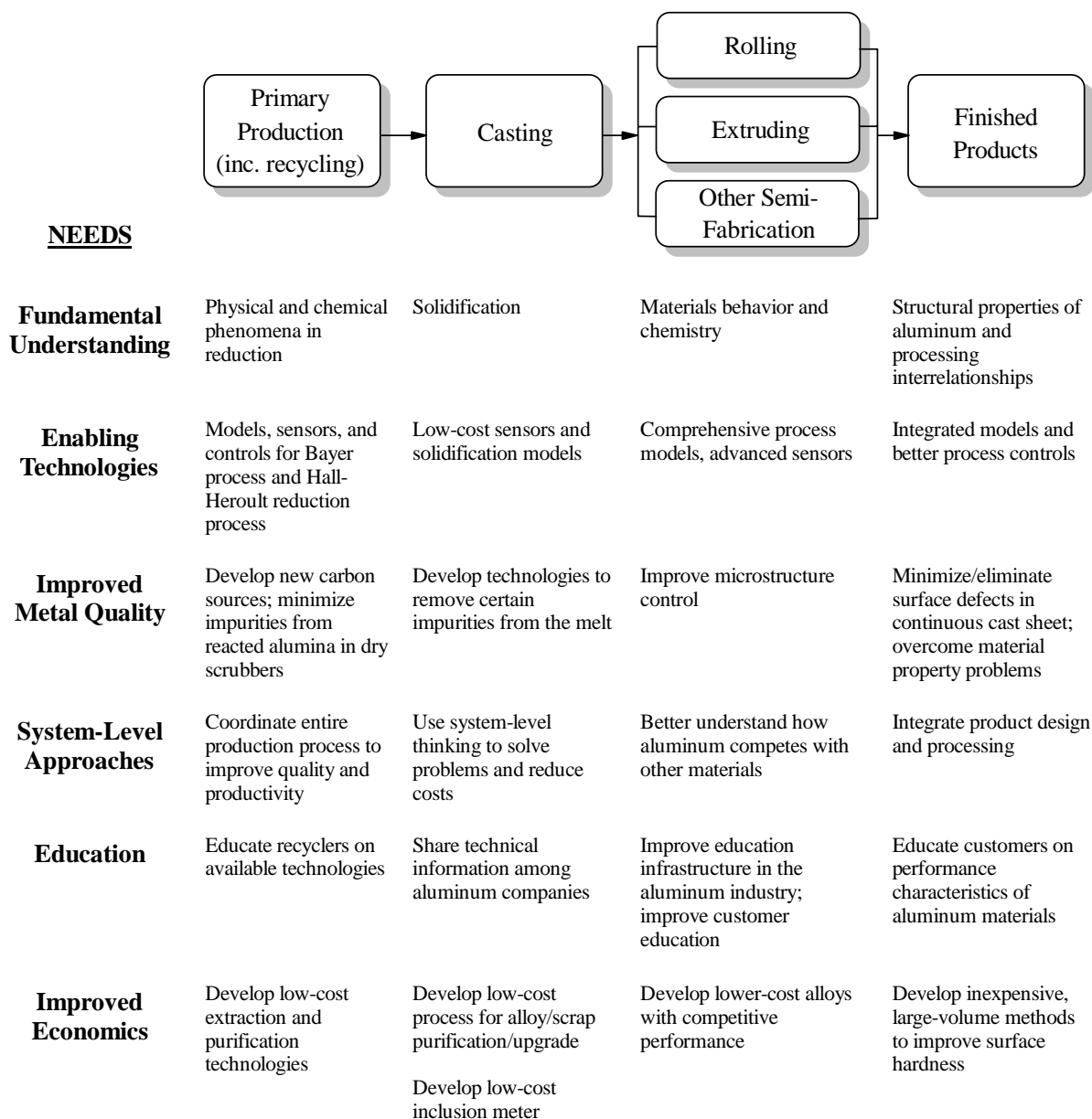


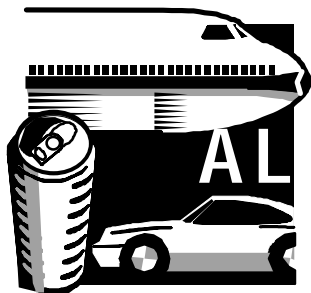
Exhibit 5-1. Common Aluminum Research Needs

Meeting the Challenge

Increasing demand for technologically complex and ecologically sustainable materials creates enormous opportunities for U.S. aluminum producers. These opportunities, however, are accompanied by formidable technological challenges. Sophisticated competitors, both here and abroad, will create strong competition in terms of price and quality of products made from aluminum as well as competing materials that may offer equal or superior characteristics. Producers will be expected to manufacture their products in an environmentally responsible manner and with concern for potential impacts on global climate change. The

new dynamics of the emerging global marketplace require that U.S. aluminum producers engage in partnerships with customers, suppliers, and government, as well as with each other to tackle demanding technological requirements.

By partnering with the Department of Energy's Office of Industrial Technologies, the aluminum industry has taken a timely and most significant step in planning the technology needs of the industry for the next 20 years. Over the next year, the development of a more detailed aluminum research agenda will help to realign research in companies, universities, and national laboratories. To ensure that this roadmap responds to customer requirements, the aluminum industry is working to improve its understanding of the technology and research needs of each of its end-use customers. It is anticipated that this roadmap will be revised and updated periodically to reflect changing market and technical issues and to ensure that the research priorities remain relevant to customer needs.



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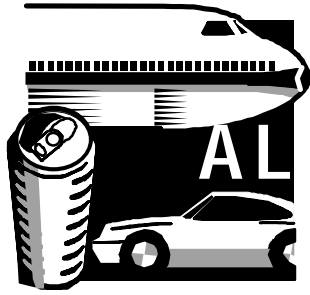
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